

Enhancement of Power System Stability Using Fuzzy Logic Based Supervisory Power System Stabilizer

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Abstract

Because of the deregulation of the power industry, environmental concerns to reinforce existing power lines or build new generation facilities, and continuous growth in demand for electric power, maintaining power system stability becomes a challenging task for engineers. A consequence of such factors is that power system damping of electro-mechanical oscillations is often reduced which could sometimes destabilize the power systems if the electro-mechanical oscillations are poorly/lightly damped.

Decentralized power system stabilizers are often used to increase damping of local oscillation modes and to some extent to increase damping of inter-area oscillation modes. However, damping of inter-area oscillation modes by the local PSS is not quite effective as for local oscillation modes. Therefore, it is necessary to implement a new control strategy to enhance damping of inter-area oscillation modes. With today's advancement of phasor measurement units (PMUs), global information, which contains valuable information about the existence of inter-area oscillation modes, could be possibly used as inputs to mitigate inter-area oscillations as the literature suggests.

The aim of this thesis is to propose supervisory power system stabilizers (SPSS) which are based on Fuzzy Logic to improve damping of such electro-mechanical oscillations in particular inter-area oscillation modes. Three different structures of supervisory power system stabilizers are presented in this thesis. The inputs to the proposed supervisory damping controllers will use global signals, speeds and their derivatives; however, the structure of the inputs to the supervisory power system stabilizers is different depending on the structural design of SPSS. The uniqueness of each SPSS type proposed is that they all make use of the same control rules regardless to which power system is applied. The robustness of such control rules and proposed SPSS are verified on three different test systems as the results of the case studies demonstrate. The time domain simulations will highlight the impact of each SPSS type on the system response.

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Acronyms

Acronym	Description
PSS	Power System Stabilizer
PMU	Phasor measurement unit
SPSS	Supervisory power system stabilizer
AVR	Automatic voltage regulator
EHV	Extra-high voltage
TGR	Transient gain reduction
AC	Alternating current
FACTS	Flexible AC transmission systems
DFIG	Doubly-fed induction generator
LMI	Linear matrix inequalities
FIS	Fuzzy inference system
GS	Gain scheduling
LFT	Linear fractional transformation
FLC	Fuzzy logic control
DAE	Differential-algebraic equations

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Chapter 1

Introduction

1.1 Thesis Background

IN the early years, electric power systems only supplied local regions which were not far from the generating stations. Therefore, the issue of power system stability or small-signal stability was not a major concern at that time. Today as the power systems have been inter-connected through overhead transmission lines to cover vast regions and even connect continents, power system stability has become a major concern for system operators and power system engineers. One of the most serious threats nowadays to the stability of the widely sparse interconnected power systems is the existence of electro-mechanical oscillations over the weakly interconnected transmission lines.

The electro-mechanical oscillations (which are also referred to as low-frequency oscillations) are of two types: local oscillations and inter-area oscillations. Of major concern today is the tie-line (i.e. inter-area) electro-mechanical oscillations, since inter-area modes can seriously limit the power flow among inter-connected power systems to meet the load demands, thus, adversely affecting the integrity of the power system suppliers [1]. Moreover, the objectionable and large tie-line electro-mechanical oscillations not only can limit the bulk power exchange between regions but also cause instability to the power systems if they are not treated and suppressed sufficiently in proper time. This can result in power outages like the blackout that struck parts of the US/Canada Western Interconnection in August 1996 [2].

The power system instability caused by the electro-mechanical oscillations, unfortunately, is not going to vanish or decrease due to the rapid increase in

demand for more power supply by booming industry and economic developments of many countries. In conjunction with that, because of political and environmental issues, such as the construction and locations of new power plants as well as the impediments of erecting new transmission facilities, it is necessary to make maximum use of existing facilities. As a consequence, transmission lines or at least some of them become more loaded than was initially planned which will lead to reduction in system oscillation damping and reduce safety margin. Therefore, to increase the safety margins as well as its stability and reliability of power system and to mitigate these low-frequency oscillations, local power system stabilizers using local signals are equipped to automatic voltage regulators of synchronous generators. However, local power system stabilizers effectively damp local modes and to some extent inter-area modes. With today's technology advancements, global information (i.e. wide-area measurements) can be readily available and used as input source to mitigate effectively inter-area oscillations, consequently, stabilizing oscillatory systems.

The realization of wide area measurement is aided by the advances and services in phasor measurement units (PMUs) which have received a great deal of interest as a synchronized measurement system of power systems. PMUs are gradually being installed on power systems in a small quantity [3]. This thesis assumes that PMUs would be available to send the global information/signals to the supervisory control centre which in turn sends the global signals to the proposed supervisory power system stabilizer (SPSS). But because there are not enough PMUs at the current time to provide the global information required by the proposed SPSS structures, the work of this thesis could not be implemented currently. However, we hope that the work of this thesis is one step ahead.

Recent studies in small-signal stability problems have been focusing its attention to use such global information as inputs for global feedback controllers to enhance small-signal stability. Hence, this will increase the

transmission capability of the power systems which are limited by the oscillatory instability. And these are the main motivation behind our proposed fuzzy logic based supervisory power system stabilizer.

1.2 Research Objectives and Scope

The distinct objectives of this research are as follows:

1. To gain an insight of the ongoing problem of small-signal stability which stressed power systems encountered due to the existence of electro-mechanical oscillations.
2. To explore proper global signals that can convey as much as information as possible about existing electro-mechanical oscillations and can be introduced as input source for proposed supervisory power system stabilizers.
3. To propose different structural designs of fuzzy logic based supervisory power system stabilizers each of which uses similar control rules regardless of its structure and applicable to different test models. The general control rules are the distinctive features of such proposed supervisory controllers.
4. To improve damping of inter-area oscillations among areas to increase line transfer capacity which is reduced by the presence of inter-area swings. It is expected to increase power transfer if you improve the stability which is a limiting factor.
5. To enhance and achieve maximum power system security and stability and prevent collapse of the networks in case of presence of disturbances and lack of proper damping by local dampers.

1.3 Thesis Statement and Contribution to Knowledge

The main contributions to knowledge of this research are as follows:

- To design and propose fuzzy-based supervisory power system stabilizers for increasing damping of tie-line electro-mechanical oscillations using global signals instead of local signals.
- To derive general control rules/strategy that would be applicable to any power system.
- To improve dynamic stability and secure operation for continuous electric power supply when exposed to some severe faults such as disconnection of lines or short circuits faults.
- To ensure damping of electro-mechanical oscillations in case of local controllers' failures. In a joint mode of operation (supervised and local power system stabilizers), priority is on traditional PSS because it is well tested, and utilities have confidence in them.

1.4 Thesis Outline

In Chapter 2, historical background related to power system stability problems and existing solutions to small-signal stability problems are explored. The working structure and idea behind local power system stabilizers are outlined. The chapter also presents a brief description of the various available working types of local power system stabilizers. In addition factors affecting the performance of local power system stabilizers will be examined.

Chapter 3 is a literature survey of supervisory power system stabilizers for enhancement of power system stability using global signals. In Chapter 4, a brief description of the theories and concepts behind Fuzzy Logic is given.

Chapter 5 will introduce three different test models that are used to validate the robustness and applicability of the different structures of proposed

supervisory power system stabilizer using the same general control rules for all test models.

Chapter 6 presents the main research contribution of this dissertation. The various techniques and methodologies of the proposed supervisory power system stabilizers (SPSS) are presented along with the general control rules. I should emphasize that the same control rules are used for each proposed supervisory power system stabilizer structure applied to different test models. In Chapter 7, the efficiency and performance of proposed SPSS are demonstrated through time domain simulations of the large test system; whereas, simulation results of the other test systems are presented in Appendix C. And finally, conclusion and suggestions for future work are given in Chapter 8.

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Chapter 2

Power System Stability

2.1 Introduction

TODAY'S increasing demand for maximum power transfer in many parts of the world is growing faster than power utilities can handle or even expand. As a result of deregulation of the electric power industry, independent power utilities are connected together over extremely long transmission lines for transferring large amount of bulk power to different regions to meet local energy demands. In addition, such large interconnections of different control regions can provide means to enhance network security and economy of operation [1]. However, these interconnections come at the cost of the power systems becoming more complex networks that have a lot of dynamics involved depending on their size: small power systems have hundreds of transmission lines; whereas, large power systems such as the US/Canadian interconnected network have thousands of transmission lines. Unfortunately, the complexity of the stability problems to maintain optimal power system security and reliable operation has amplified as well. In this chapter, low frequency oscillations and brief history of power system stability problems are illustrated, and the contemporary solution to remedy power swings is explained.

2.2 Electro-Mechanical Oscillations

Although not over loaded, nterconnected power systems (ties) are weakly coupled compared to the connections within each power system. With the high inertia of each system connected to the interconnected ties and low

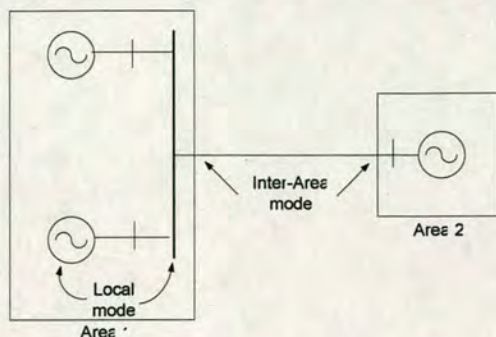
synchronizing torques among the weakly coupled interconnected ties, low frequency oscillations are found to exist [2, 3]. Electro-mechanical oscillations are results of generator rotor swings in the frequency range of 0.1 – 3.0 Hz and are classified according to how they are formed and where they are located in the power system.

During a disturbance such as a sudden load increase, the energy stored in the magnetic field of each machine is released first through generators' rotors since sudden step change in turbines to increase electric power is not possible. The released kinetic energy is exchanged between the power networks in the form of electric power flowing through transmission lines. The share of load increase in the network is shared by each machine in the network according to its unit size and by the Thevenin impedance at its terminal. Each generator's rotor will oscillate at a frequency of response due to the interactions among power system elements until the damping forces damp out all these oscillations. However, if the damping forces are not adequate enough because of:

1. An almost disappearance of effectiveness of damper winding in a system generator (as it is inversely proportional to the square of the effective external impedance plus stator impedance) [4].
2. The negative effect of high-gain AVR's on damping torques with absence of any damping controllers [5].

These oscillatory modes might grow in magnitude exponentially and render the system to be unstable. They are reflected in many variables most noticeably generators' rotor speeds and power flow in tie-lines (i.e. oscillation modes are superimposed on tie-line power flow).

Electro-mechanical oscillations are of various types. However, two modes of oscillation generally exist in the power systems, and they are local (plant) modes and inter-area modes, Figure 2.1:



2.1 Oscillation modes in interconnected power system

Local modes are defined as rotor swings of a synchronous generator against the rest of the power system, and they are influenced by the states of the local area. Typically, the local mode has a frequency range of 0.9 – 2.0 Hz. For inter-area modes which are of special interest here, they are phenomena characterized by swinging of a group of generators in one region coherently against a group or groups of generators in other areas of the system. They are influenced by global states of large interconnected power systems and are more complex in nature and require a detailed representation of the system network. Oscillations that could be neglected for each generator could be compounded to produce significant oscillations in the tie link which are very significant compared to the ratings of the generators. Normally, the frequency range of inter-area modes is between 0.1 – 0.9 Hz.

Low-frequency inter-area oscillations, which receive more attention because of their inherence to the weakly tie lines connecting power systems, are affected by the system structure, generator modelling, excitation type, and system loads. Recent studies show that the natural frequency and damping of inter-area oscillations depend not only on impedance of the tie lines but also on the power transfer [6, 7]. So as tie lines get weaker (impedance of the lines increases) and more power is transferred, the natural frequency and damping of inter-area modes are reduced. Experience suggests that a generating unit experiences only a portion of the total magnitude of the power oscillations in the inter-area modes, so damping controller equipped to this generating unit can only contribute to the damping of inter-tie modes in proportion to the

power generation capacity of the generating unit relative to the total capacity of the area of which it is part of [8].

In addition to local modes and of special interest to inter-area modes, there exist other types of electro-mechanical oscillations, and they include exciter modes, intra-plant modes, and torsional modes which are caused by interactions of mechanical and electrical modes of turbine-generator system.

2.3 History of Power System Stability Problems

In the early days of interconnected power systems, the most widespread problem of small-signal stability form is the loss of synchronism following a fault due to the lack of synchronizing torque. The development of fast, automatic voltage regulators (AVRs) acting on the generators' excitation systems has provided an increase in the synchronizing torque. Although, AVRs improved the steady-state stability of power systems, they could not maintain stability during transient conditions so it becomes a major source of concern. The addition of AVRs to generators' exciters had an adverse effect by causing a reduction in damping torque (T_d) provided by the damper windings of synchronous generators. The adverse influence of AVRs in conjunction with a weakening of transmission systems relative to the sizes of the generating stations has caused the interconnected power systems to be prone to oscillatory stability due to the lack of damping power for damping low-frequency electromechanical oscillations [6].

In weakly interconnected power systems, hundreds to thousands of low frequency oscillation modes are present. And these persistent low frequency oscillations are potential limiting factors to secure operations of the power system and maximum power transfer. They can also cause power outages if they grow uncontrolled and undamped in real time [9]. So dynamic stability of power system that deals with the study of power systems behaviour under conditions such as changing loads or generations or short circuits on

transmission lines can be a great obstacle for efficient energy transfer when there are weak transmission and heavy loading [10].

One way to combat the growing concerns of inhibiting effects of the low-frequency oscillation (i.e. small-signal stability problem) is by adding extra-high voltage (EHV) transmission routes to suppress these electromechanical modes, hence, increasing power system security as more routes are available for power transmissions. However, due to stiff environmental regulations and the high cost of building new EHV, a major approach in dealing with low-frequency oscillations is the contemporary solution of adding a supplementary control loop known as a power system stabilizer (PSS). The addition of PSS to the excitation system of a synchronous generator provides a supplementary damping source by producing a damping torque in phase with generator's rotor speed deviation ($\Delta\omega$) to compensate for the phase lag between exciter's input and generator electrical torque.

2.4 Power System Stabilizers

Reliability and stability of a power system are major factors for continuous electricity generation as mentioned before [11]. The capability of a power system to remain stable over a wide range of frequency and operating conditions depends to a large extent on the control available on the system to damp the electro-mechanical rotor oscillations [10]. The damping of the power swings not only ensures transient stability, small-signal system stability and security but also extends the capability of the power transfer limit over the transmission lines [2, 8].

In a power system, the electrical torque of a synchronous machine can be resolved into two parts after being subjected to perturbations:

$$\Delta T_e = T_s \Delta \delta + T_d \Delta \omega \quad 2.1$$

where,

$T_s\Delta\delta$ represents a synchronizing torque which must be in phase with rotor angle perturbation $\Delta\delta$ (i.e. the angular displacement of the generators' rotors). Insufficiency of the synchronizing torque component could cause the machine(s) to lose synchronism with the rest of the power system. Protective measures must be taken to trip the machine(s) to protect the machine(s) as well as the power system. So in any case of angular displacement increase between generators, the electric torque is produced attempting to reduce the angular displacement and keep the generators in synchronism [3]. But there are special cases where the synchronizing torque is unable to keep the generator(s) in synchronism due to a prolonged three-phase fault on transmission lines (large disturbance). In a small-disturbance, the synchronizing torque keeps the generators in synchronism; however, the generators will exhibit oscillations which require immediate damping to keep the integrity of the interconnected power system stable and intact. That is where the damping torque comes into play.

$T_d\Delta\omega$ represents the damping torque component which must be in phase with rotor speed deviations $\Delta\omega$ so that the electromechanical oscillations are well damped to maintain small-signal stability. The lack of sufficient damping torque will cause the system to be oscillatory and growing in magnitude eventually causing instability and even causing unit(s) to trip in some severe situations [10].

From the explanation above, the small-signal stability problem can be attributed to either lacking a synchronizing torque or a damping torque [12]. But current small-signal stability problems that are faced daily by power systems are mostly due to the insufficiency of a damping torque to eradicate rotor oscillations that power system exhibit. Such necessity for a supplementary damping controller has led to the development of PSS to act upon AVR and the exciter of a synchronous generator. Therefore, the primary objective of PSS is to improve small-signal stability by adding a stabilizing

signal to the voltage reference signal. Nonetheless, experience has shown that PSS can impact the generator-power system transient performance in some circumstances [13].

In spite of relative simplicity, power system stabilizers may be one of the most misunderstood and misused pieces of generator control equipment. By the mid 1960s, several researchers had been successful in implementing additional supplementary feedback controllers to enhance damping of rotor oscillations [14], and today PSS has become an effective means to provide damping to low frequency oscillation especially with the new advancement in technology and development of automatic voltage regulators and fast acting exciters.

PSS can be used with slow or fast, rotating or static exciters. PSS can have a major influence in improving overall system stability/dynamic stability with static exciters that have the characteristics of high initial response, in particular thyristor exciters [15, 16]. Hence, it is evident that proper choice of PSS and excitation systems ensures a practical approach to improve system stability. Different types of exciters and AVR's have been studied and developed and are ready to use for large scale system stability studies, and they can be found in a IEEE standard [17]. In some situations, slow inter-area swings are dominant in power system transient response, and it is recommended that a discontinuous excitation control be used along with PSS to improve transient stability [10]. As a precaution, some power utilities equip their generating units double AVR and PSS in case one set breaks down, the second set which must track the first set will get engaged; this will improve reliability.

Although there are numerous control schemes for PSS that can be based on artificial intelligence (neural network, fuzzy logic), or based on new techniques (LQG/LTR, H_2 , H_∞ , and μ -synthesis) or based on adaptive schemes [18], the most widely and commonly used power system stabilizer scheme is the conventional power system stabilizer shown in Figure 2.2 [19].

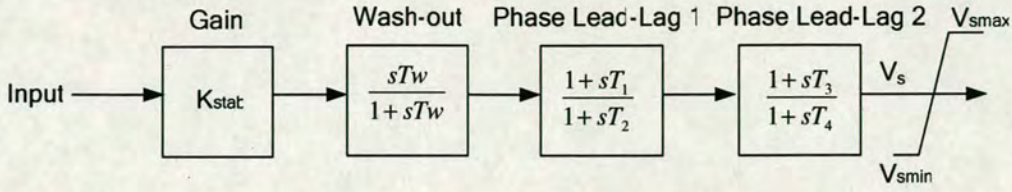


Figure 2.2 Conventional power system stabilizer

In this figure, the inputs of stabilizer could be of various types: rotor shaft speed, generator terminal bus frequency and/or electrical power or accelerating power [14] which are discussed in more details in the upcoming sections. The output V_s is a stabilizing signal added to the excitation system of a synchronous generator as in Figure 2.3.

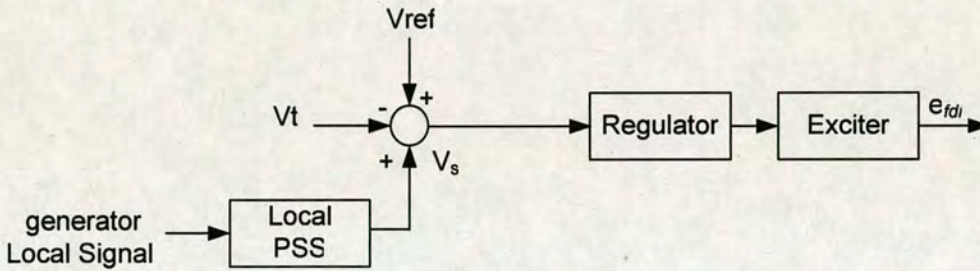


Figure 2.3 Excitation system with power system stabilizer

The PSS can be designed to match the phase lead over a wide range of frequencies, which is highly recommended so that other oscillation modes will not be destabilized. It can also be designed to match the ideal phase lead close to that of the plant mode. In the latter case, the PSS will have a detrimental affect on the power system depending on the input to the PSS, explained in more details later. Nevertheless, compared to its high damping influence on local modes, PSS effectiveness on inter-area oscillations is much less which is the driving force behind this research. To best obtain a proper prediction of power system stability oscillations, the models of the generators and their controls such as excitation model must be known.

2.5 General Procedure for Selecting PSS Parameters

In order to have an effective power system stabilizer capable of delivering optimum damping of electromechanical oscillation, the supplementary control loop must be carefully designed and tuned [3], and its parameters must be properly selected and determined based upon input signals to the PSS, methods of deriving input signals, control method, and accounting for other modes and controls. Experience suggests that satisfactory, robust PSS performance can be obtained if the external system reactance is in the range of 20-80% of the unit rating [8]. Proper tuning of PSS parameters not only damps the rotor oscillations but also maximizes power transfer capability (which is limited by oscillatory instability as stated before). Unfortunately, in reality optimum tuning of PSS to achieve effective damping of both local and inter-area oscillations might be difficult to achieve (explained below). The following which refers to Figure 2.2 explains in detail the general procedure to determine PSS settings and tunings.

2.5.1 Phase-Lead Compensation

The power system stabilizer will damp the rotor electromechanical oscillations, and thus improve small-signal stability, if a damping torque produced by the stabilizer is in phase with the rotor speed variations and acting on the machine's rotors [8, 14, 16]. For any input type based PSS, the transfer function of the PSS must compensate for the gain and phase characteristics of the excitation system, generator, and power system which collectively determine the transfer function from PSS output to the component of electrical torque which can be modulated via excitation control. One must bear in mind that this transfer function of the plant denoted $GEP(s)$ is strongly affected by gain of AVR, generator power level, and ac system strength. As ac power system gets stronger, more phase lag must be overcome than with a weak ac system; this problem is amplified even more with high gain AVR since cross-over frequency of AVR loop is in the range of oscillation

frequencies of interest [8]. Another important issue dealing with the phase lead is that unnecessary filtering in the PSS signal path can add delays and thus obtaining the right amount of phase lead by PSS will be difficult to achieve.

The phase compensation by PSS is achieved through two lead-lag blocks shown in Figure 2.2. In situation for local mode damping, the signal conditioning circuit lead time constants T_1 & T_3 are used to compensate for the excitation system phase lag; whereas, the lag time constants T_2 & T_4 are set about 8 – 10 times smaller than T_1 & T_3 [20]. Careful consideration must be taken into account when compensating for the phase lag between excitation system and generator electrical torque since the phase to be compensated changes as the conditions of the power system change, so a compromise is inevitable which could result in a slight under-compensation, which is preferred to overcompensation. With under-compensation, damping and synchronizing torques are increased; whereas, when there is an over-compensation, the synchronizing torque as well as the damping of inter-area oscillations will be adversely affected, and that could threaten the stability of the power system especially if the dominant oscillations are inter-area oscillations modes [19, 21]. So attempts to overcome too much phase lag in the exciter by PSS can cause a very noisy PSS signal and can cause substantial adverse affects.

A difficult task for PSS is when dealing with smaller machines that are usually equipped with slowest exciters and are located near noisy load centres. Because of the slowest exciter, these types of machines require very large phase lead compensation by PSS; however, due to its close location to the noisy loads, the PSS effectiveness is almost unnoticeable as low PSS gain must be used to. In such cases, transient gain reduction (TGR) may be better off to be used on the excitation system than the use of PSS. More about TGR is explained later [22].

There are different programs available nowadays that can be used to determine the phase lag between the exciter input and synchronous machine electrical torque, one of which is SIMULINK. Practical experience has shown the maximum phase lead/lag stages that can be used must not exceed four stages, each of which provides a maximum of 60° of phase lead to ensure a physical realizable a which is a constant defined as [23, 24]:

$$a = \frac{1 + \sin(\phi_m)}{1 - \sin(\phi_m)} \quad 2.2$$

where Φ_m is the phase lag to be compensated by PSS.

2.5.2 Stabilizing Signal Washout

The washout signal is used as a high-pass filter to filter out the DC component which could change the synchronous machine terminal voltage as steady speed changes. Without it, the steady speed changes will modify the field voltage which will in turn modify the generator's terminal voltage. The washout time-constant (T_w) is not critical, and its range is 1 to 20 seconds. However, T_w must be ensured to be long enough to pass stabilizing signals/oscillation signals in rotor speed unchanged, but also proper care must be considered since too long stabilizing signal can have a negative effect by passing unwanted frequencies which cause large voltage excursions during islanding conditions [14].

For inter-area oscillations, the washout time-constant should be 10 seconds or higher to reduce phase-lead at low frequency, because too low value of washout time constant will result in a decrease in the damping of inter-area oscillations and a decrease in synchronizing torque component at inter-area oscillation frequencies which will have a detrimental effect on transient stability in situations with dominant inter-area swings [10, 13, 16].

2.5.3 Stabilizer Gain (K_{stab})

The gain of stabilizer has a key role in damping electromechanical rotor oscillations. The higher the gain is, the better damping PSS delivers, and the proper method to determine the best gain value (K_{stab}) is by observing the power system stabilizer performance and its effect over a wide range of values provided proper representation of individual units equipped with PSS. Ideally, its value is set to provide maximum damping; however, PSS gain is usually limited by other considerations: PSS gain must be set to provide a satisfactory damping of all critical oscillation modes to which it is designed without any compromise to the stability of other modes such as exciter modes or transient stability. In case PSS destabilizes exciter modes, the value of the PSS gain must be decreased to 50% of the original value (that had a destabilizing effect on exciter modes) [25]. In addition, its value must not cause any amplification of the input signal noise [10, 14, 19]. Not only does the type of PSS input have a detrimental effect on the PSS gain, but it also affects the choice of exciter scheme chosen to which the stabilizing signal is connected.

A common practice in industry is to use transient gain reduction (TGR) in order to reduce exciter gain. It is observed that using PSS with TGR scheme requires that stabilizer gain be almost double the gain against that without TGR. The increase in PSS gain will result in enhanced damping of oscillation modes, especially local and inter-area oscillations. Without PSS ($K_{stab} = 0$), TGR improves local damping but decrease inter-area damping, and this is of interest since reduction of transient gain is often recommended as a means of improving small-signal stability in the absence of PSS [19, 20].

2.5.4 Stabilizing Output Limits

A Stabilizing output limiter is used at the final stage of PSS to restrict the stabilizing signal (V_s) to prevent the synchronous machine's terminal voltage

fluctuation in the case of transient stability conditions [26]. Figure 2.3 shown previously illustrates where the stabilizing signal is injected.

According to past experience, the upper positive limit is set between 0.1 – 0.2 pu range in order to allow a large contribution from the PSS during large swings; however, it is necessary to limit the generator terminal voltage to its maximum allowable value that is in the range of 1.12 – 1.15 pu by the use of terminal voltage limiter.

For the negative side of the output limits, the appropriate set value is between -0.05 to -0.1 pu so that sufficient control range is provided while providing satisfactory transient response. Moreover, it will reduce the likelihood of a unit trip due to a stabilizer failure [19].

Having established the design procedure for PSS, possible interactions of PSS controls with other operational control which are a part of the excitation system or controls acting on the external system such as HVDC, SVC, etc. must be considered and coordinated with PSS since these controls might improve damping for best possible operation [16]. In addition, there are critical situations that PSS might lead to instability instead of stability: the most critical case is when there is a loss of local generation where the frequency and voltage drop, and the power tends to be increased as a result of governor action to restore frequency. The PSS will mistakenly cause large excursions in generator voltage in the downward direction instead of upward direction (i.e. move the voltage in the wrong direction), and if the voltage is significantly reduced to a dangerous level the system can lose stability particularly if it is close to the critical clearing time in some cases of particular disturbances. Thus a modified PSS with limit algorithm to the wash-out stage must be considered to alleviate the severity of the terminal voltage drop due to adverse PSS impact on voltage swings [13].

2.6 Types of Power System Stabilizers

This section will highlight the different kinds of well-known PSSs. Drawbacks and problems encountered impacting the performance of each type are explained.

2.6.1 Speed-Based ($\Delta\omega$) PSS

Often referred to as delta-omega PSS, this PSS has been widely used in hydraulic units since the mid of 1960's. The speed-based PSS is considered to be the building block for the main components of all power system stabilizers currently being used.

The input to PSS can be obtained through the use of a transducer consisting of a tooth-wheel and magnetic speed probe supplying a frequency-to-voltage converter. The obtained signal is filtered using a high-pass filter (wash-out) so that PSS will not alter generator terminal voltage for slow changes (steady state) in the shaft speed as it could take place during power system voltage excursions. The PSS stabilizing signal is injected to the excitation system to produce the required variation in the exciter output and field voltage. An important consideration is to reduce low frequency noise caused by the shaft run-out (lateral movement) by summing the outputs of several picks around the shaft. This has been proved to be expensive and lacks long term reliability [14].

For thermal units, the use of a shaft-speed based PSS must be accompanied by the use of a torsional filter: careful measures must be taken to provide adequate filtering of torsional components; if they are not properly filtered, PSS will cause instability of the torsional modes while low frequency oscillation modes are damped. Torsional oscillations are phenomena related to the rotating masses of the system and loosely coupled to the outside world through the magnetic field and system reactance at the generator output, and their magnitudes have the potential to grow excessively when the speed is

chosen as a stabilizing input [27]. As a result, the use of speed-based PSS has a limitation due to the requirement to use torsional filters which will introduce a phase lag at lower frequencies. This in turn will reduce stability of the exciter modes, thus, restricting the stabilizer gain maximum value. And if the PSS is designed to match the phase lead at a frequency close to that of local modes, also the intra-plant modes will be destabilized because of insufficiency of phase lead at high frequencies since intra-plant modes do occur at high frequency [14, 25]. The other draw back of shaft-speed stabilizer is that the stabilizer must be custom-designed for each type of generating unit depending on its torsional characteristics [11].

Nonetheless, with well-tuned PSS parameters, the conventional performance of PSS can be acceptable over a reasonable range of system operating conditions. But as the speed is an input to this type of PSS, the PSS damping of inter-area modes of oscillations is reduced as the system impedance increases. Any increase of the stabilizer gain at this stage to increase damping power will be encountered by an increase in the negative synchronizing torque which is detrimental to overall performance and stability of the power system and will cause a decrease in the natural frequency of oscillations and reduce inter-area oscillation damping [6]. Therefore, it is recommended to set the gain of speed based PSS under a strong ac system because of the fact that under strong ac system, more phase lag is required to overcome than with a weak ac system [8].

A possible solution with speed-based PSS under weak tie connections is to augment the control scheme of the conventional PSS by connecting an additional control loop in parallel with it. This proposed solution enhances overall performance for weak tie links by coordinating PSS performance with the d-axis damping contribution that can be influenced only by the excitation control; local oscillation modes which occur at higher frequency are not adversely affected by the additional parallel loop. The electromagnetic coupling of the system grid with the generating unit(s) to which the PSS is

equipped is improved because of the positive contribution of the proposed method to the synchronizing torque [6]. Furthermore, the improved PSS can alleviate the constraints imposed on overhead transmission lines to restrict power transfer capability for dynamic instability reasons.

2.6.2 Frequency-Based (Δf) PSS

As the name indicates, the input signal to this type of PSS is the terminal bus frequency which can be injected directly to the PSS, and sometimes the generator terminal voltage and current are combined to approximate the machine's rotor speed and use it as a signal to the power system stabilizer. The generator bus frequency is the rate of change of bus angle.

Frequency-based PSS has an advantage over the speed-based PSS when it comes to inter-area oscillation modes: its sensitivity to rotor oscillation modes between large areas separating parts of the power systems is more than its sensitivity to oscillation modes of individual generating units even within a single generating plant. And its sensitivity increases as the ac transmission system gets weaker which offsets the reduction of gain from stabilizer output to electrical torque that results from weak ac transmission systems. Therefore, its contributions to inter-area damping exceeds in magnitude the contributions of inter-area damping that can be obtained by shaft-speed PSS. This explains why frequency-based PSS is preferable a supplementary control loop to produce a damping torque when the major concern and dominant oscillation modes are low frequency inter-area oscillations [8, 14].

A drawback of frequency-based PSS is the requirement to use torsional filters occasionally. Unfortunately when frequency-based PSS is equipped to thermal units, the frequency signals measured at their terminals will contain torsional modes unless they are filtered out using torsional filters [14]. A second drawback of using frequency as an input to PSS is the large frequency transients that will have detrimental consequences on the generator's field voltage and output quantities. This is because of the phase shifts in the ac

voltage resulting from modification in power system configurations. Moreover, special attention must be paid to noise problems with frequency-type PSS. Noise arises from large phase compensation and the susceptibility of frequency signals/transducers to power system noise caused by large industrial loads such as arc furnaces [13, 28].

If the frequency-based PSS is designed to match the ideal phase lead over a wide-range of frequency or designed to match the ideal phase lead at a frequency close to that of local modes, the low frequency oscillations (i.e. inter-area and local modes) will be stabilized. While it helps damping the inter-area oscillation modes, the damping of the exciter modes is greatly reduced especially under a weak ac system. The destabilizing effect by PSS on the exciter and intra-plant modes can be prevented by restricting the allowable gain of PSS to 50% of that which causes exciter mode instability as stated before. The immediate effect of such gain reduction is to limit PSS effectiveness with frequency input type PSS compared with other type inputs [25]. In practice, frequency and power are significantly related to a generator speed and acceleration, respectively. Any changes to their gains will impact the effectiveness of the PSS phase lead [29].

2.6.3 Power-Based (ΔP) PSS

Since speed-based PSS and frequency-based PSS have been proved to have inherent limitations which can not only degrade the performance of power system stabilizer by reducing the damping required to small-signal stability problems, but also destabilize other modes of oscillations which are stable prior to the application of PSS, these inherent limitations have led researchers to a new and improved type of power system stabilizer which uses either electric power or accelerating power (P_a) as an input to the PSS.

Prior to the development of P_a as an input to PSS, in many applications electrical power (P_e) based PSS is used for small-signal stability problems. The problem with this type of PSS is not torsional oscillations which are

attenuated naturally by P_e but with the assumption that the mechanical power (P_m) is constant or neglected. This assumption is often unpractical, especially in the event of changing loads on generating units or system conditions when the mechanical power changes. Under these circumstances, P_e will be confused by PSS as P_a due to the absence of mechanical power signal and spurious stabilizing signals is created. This in turn causes transient oscillations in voltage and reactive power [5, 16, 27, 30]. So it is recommended that P_e not be used as an input to PSS because of power ramping which will produce severe under or over voltages, thus, forcing the disconnection of PSS [29]. The effect of mechanical power changes can be reduced by using a limiter to limit PSS output, using high-pass (washout signal), low PSS gain, or isolate PSS or disconnect it when rapid mechanical changes take place [31].

Previous design methods to deduce and measure the accelerating power for different type of units are of complex nature and require custom-design for each location. This has lead to the necessity to develop a new design method which indirectly derives the accelerating power to be injected as PSS input [31], and the IEEE standard PSS2A model used to represent this design is shown as Figure 2.4 [32].

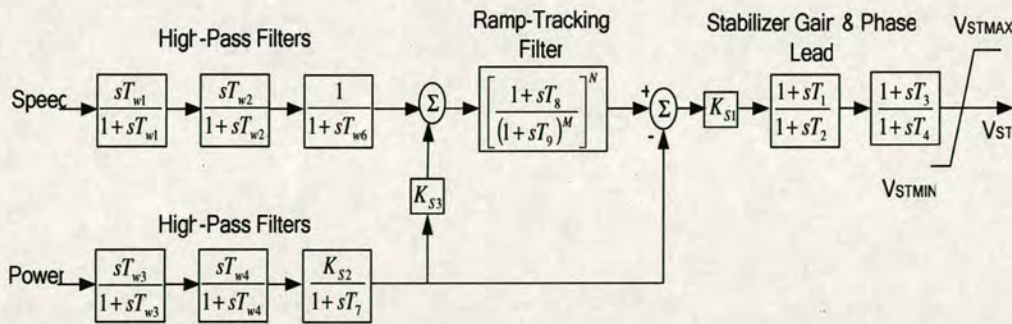


Figure 2.4 IEEE Standard PSS2A

For Delta-P-Omega stabilizer, the inputs are shaft speed and electric power [19]. The working principle for this type PSS is based on the swing equation shown below where the damping factor D is considered to be equal to zero since the contribution of damping due to damper windings is generally small:

$$\Delta\omega_{eq} = \frac{1}{M} \int (\Delta P_m - \Delta P_e) dt \quad 2.3$$

Where,

M = inertia constant, $2H$.

ΔP_m = change in mechanical power input.

ΔP_e = change in electric power input.

$\Delta\omega_{eq}$ = derived or equivalent speed deviation.

In a per-unit system and at rated speed, torque and power can be considered equivalent in value [33]. The aim first is to derive $\Delta\omega_{eq}$ so that it does not contain torsional modes which are attenuated automatically in the ΔP_e signal. Having deduced the equivalent rotor speed deviations, the integral of mechanical power is established and is related to shaft speed and electrical power as follows:

$$\int (\Delta P_m) dt = M\Delta\omega + \int (\Delta P_e) dt \quad 2.4$$

The simulated mechanical signal shown above contains torsional oscillation modes which require filter to be used to remove these oscillations. But because mechanical power changes slowly even if a valve mechanism is fast (P_m moves in ramp rather than step functions), a low pass-filter can be used in the path of the simulated integral of mechanical power to filter out any torsional oscillations. High-pass filters can also be included in the path of the two inputs so that steady-state changes (low frequency changes) are removed and only frequencies of interest are cleared to pass. Since P_m does not change rapidly and moves in ramp rather than step functions, a ramp tracking filter (multi-pole low pass filter) is used to track and pass slower changes in P_m . Having derived the integrals of mechanical power and electrical power, they are subtracted from each other at the summing junction to deduce the required integral of accelerating power as an input to PSS [14, 30, 33].

With power as an input to PSS, the need to use a torsional filter is avoided in the main stabilizing path, and therefore it will not introduce any phase lags to

the system and will not destabilize the exciter modes that have prevented PSS to be fully utilized (as a result of stabilizer gain reduction to avoid exciter mode stability problems). Thus, more damping can be provided with the use of power-based power system stabilizers. Another advantage of having power as an input to PSS is that power provides 90° of phase lead to the excitation system since accelerating power precede changes in speed by 90° , as in Figure 2.5. Less phase lead is required with power type PSS than with frequency or speed type PSS. Because of the 90° phase lead at all frequencies, power based PSS is recommended to be used when the phase lag to be compensated by PSS is substantial.

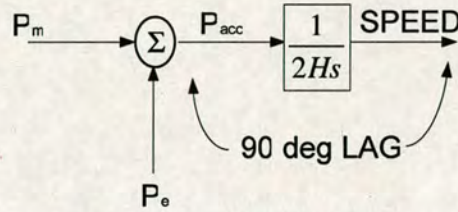


Figure 2.5 90 deg. phase lead by power as input to PSS

where,

P_{acc} : accelerating power,

P_e : Electrical Power, and

P_m : Mechanical Power.

Less phase lead compensation should help reduce PSS output noise, and the compensation angle under the oscillation frequency and lag angle of the generator excitation system should satisfy the following criteria [15, 20, 22]:

$$\phi_{pss} + \phi_{AVR} = 90^\circ \quad 2.5$$

where,

ϕ_{pss} : the phase lead provide by PSS

Φ_{AVR} : the phase lag of the excitation system to be compensated by PSS.

The impact of power based PSS on electromechanical oscillations can be examined through the root locus: a straight line departure to the left plane indicates the stabilizer has a good phase compensation in particular for inter-area oscillation modes and will not have an adverse effect on the synchronizing torque component in the process since too high PSS gain could deteriorate the synchronizing torque. With power type PSS, a common practice by the industry is to set its gain at a full load and connected with a strong power system to provide as large damping as possible so that in the case of a weak system, PSS performance can be satisfactory [8].

2.7 Power System Stabilizer Performance

The ability of power system stabilizers to provide theoretically robust, optimum damping to rotor oscillations over a wide range of frequency and operating conditions not only depends on tuning procedure as explained previously but also on other factors such as locations of PSS, voltage characteristics of system loads, and external reactance of the power system [34]. Analysis tools can be utilized to best determine the influence of such factors on performance of PSS to maintain small-signal stability.

2.7.1 Analysis

Today there are numerous analysis tools available to study the stability of the power systems and to determine the oscillation modes and damping factor, frequency of oscillations, etc. Some of these analysis tools are MODAL technique and eigenvalue analysis. It is reported in some literature that the proper way to effectively determine how some factors influence the

performance of damping controllers is to study their effects on small power systems, then findings and solution could be applied to large system [7, 34].

2.7.2 Locations of Power System Stabilizers

To suitably determine proper locations of PSSs, electro-mechanical oscillations modes of areas involved must be analyzed through suitable analysis tools bearing in mind oscillation modes in one part of the power systems might excite oscillation modes in another part of the power system due to resonance (i.e. relative closeness of oscillation frequencies). This kind of situation might distort the oscillation mode shapes and participation factors which represent eigenvalue sensitivities to changes of the diagonal elements of state matrix. It will result in a misleading picture of the system behaviour. This misleading phenomenon mostly influences local oscillation modes to a large extent.

In such situations, the generating units in one area could be significant participants in the local modes of other areas. In reality this is unusual since intuitively it is highly unexpected that local modes of two different parts of weakly coupled power systems to interact. Such unusual interactions mean meaningless non-unique eigenvectors with equal eigenvalues. Also the participation factors will not convey the real picture of the sensitivity information. Besides, the residues which show the contribution of oscillation modes to a transfer function can be misleading and can lead to ineffective PSS since they determine the proper location of PSS to provide optimum damping for local oscillations. However, in some cases the best location of PSS to control the electro-mechanical oscillations is not necessarily the plant where the mode can be observed [22]. To analyze the system stability properly in this situation with eigenvalue analysis, the inertia of the generating units involved in one area can be modified to produce unique eigenvalues, eigenvectors and residues, thus, proper location of PSS to damp local modes can be properly chosen [34].

2.7.3 Influence of Load Types

As load increases without any addition of power plants or extra high voltage (EHV) transmission lines, the imbalance of power transfer causes large power flow on the EHV lines which further deteriorates damping of electromechanical oscillations [9]. Therefore, for stable operation of the power system, the electrical output of the generating units must match the electrical load on the system. Hence, load characteristics have a great influence on the system stability, and proper modulation of the loads is important [10].

It is shown that damping of the inter-area oscillations are far more affected by the location and characteristics of the system loads than local oscillations. For PSS to increase damping of inter-area oscillations, it must modulate properly the system loads; otherwise, PSS performance in damping inter-area modes can be adversely affected: with constant power loads that are used to test the ability of PSS, the damping of inter-area oscillations by PSS is significantly reduced than with constant impedance loads. In other words, when the voltage of the bus load is held constant or the load does not vary with voltage, PSS effectiveness on inter-area oscillation damping is reduced considerably [34].

The reduction in inter-area oscillation damping can be attributed to the negative damping and synchronizing torques caused by constant power loads; on the other hand, positive damping and synchronizing torques are improved with constant impedance loads. Unfortunately, a realistic case of constant power loads is the use of induction motor loads which dominate industrial loads nowadays and use 90% out of 50–60% of electricity consumed by electric motors [5]. So the more induction loads that are placed on the power system, the more the loads will look like constant power loads, and the more deterioration of PSS ability to damp inter-area oscillations which will definitely endanger system stability.

As far as the local modes are concerned, they are insensitive to the load models used to design PSS, although there has been an observation that with

constant power loads, a slight improvement of local mode damping by PSS is obtained [34]. Finally, when it comes to loading conditions, small load adjustments in a power system could cause under-damped power oscillations on the transmission lines and could cause customer load loss and tripping of the generating units [22].

2.7.4 TGR Influence on PSS

The use of TGR as means of exciter gain reduction at a higher frequency must be carefully considered according to the overall power system dynamic stability performance. In some situations dealing with smaller machines to which slower exciters are equipped and are located near noisy load centers, it is found the use of TGR might be better off to be used on the excitation system than the use of PSS. That is because with slow exciters, these types of machines require very large phase compensation by PSS; however, due to its close locations to the noisy loads, the PSS overall effectiveness is almost unnoticeable as low PSS gain must be used to prevent significant noise problems [22].

Although as reported previously, TGR used with fast-excitors will allow the gain of PSS to be doubled which translates into increase damping of electro-mechanical oscillations, the use of TGR has also some adverse consequences especially on inter-area oscillation damping.

In [19], it is found that in the case where TGR is not used, the increase in PSS gain will lead to damping enhancement as well as transient stability. On the other hand, while an increase PSS gain with the use of TGR enhances damping, this might lead to a deterioration of transient stability. So a compromise might be necessary in selecting appropriate PSS gain. In situations the effect of losing PSS without the use of TGR on one or more units is less severe on inter-area oscillation damping than with TGR. In addition without the use of TGR, PSS gain and output limits are lower than with TGR,

and the overall damping performance is the same in some situations; thus, deterioration to transient stability is less.

2.8 Other Sources of Supplementary Damping

Since electro-mechanical oscillations are inherent in weakly-coupled power systems and further damping requirements are essential, different sources of supplementary damping are sought for two of which are high-voltage DC links (HVDC) and flexible AC transmission system (FACTS).

2.8.1 High-Voltage Direct Current Links

The use of HVDC is steadily on the rise because of its advantages over ac links in special situations. In HVDC, the control signals used are bus frequency deviations or power flow in the ac transmission links [35]. With HVDC links, rectifiers and converter controls are used to rectify the AC voltage and transmit it to DC which is then converted back to AC. So the power flow in HVDC links is controlled in contrast to ac lines; therefore, HVDC links can have a significant impact on small-signal stability of the ac power system.

For submarine cables longer than 50 km and for overhead transmission lines longer than 600 km, HVDC links are used instead of ac links due to the absence of intermediate reactive compensation stations. Due to its asynchronous nature, it is found that dc links can be feasibly used to connect two power systems; otherwise, they will be hard to connect through ac links because of the instability problems or having different nominal frequencies such as 50 and 60 Hz [10, 36]. So the use of dc links can provide a positive impact on the performance of the overall ac/dc system.

2.8.2 Flexible AC Transmission Systems (FACTS)

FACTS are primarily based on the advancements of power electronics technology and are developed in the late 1980s. They are used to control electro-mechanical oscillations through the power flows in the transmission systems:

$$P = \frac{V_1 V_2}{X} \sin(\theta_1 - \theta_2) \quad 2.5$$

where X is reactance of the line and V_1 , V_2 , θ_1 and θ_2 are the magnitude and phase angles of the voltage at both ends of the lines. The FACTS devices enable the control of the power flow through different variables or parameters, thus, it can allow the parallel lines to be fully loaded in conjunction with additional damping controllers, such as PSS. Another advantage of FACTS is its fast response characteristic which can make it feasible to be used for power system stability enhancements. Nonetheless, the primary drawback of FACTS is its requirement for sophisticated protection of large and complex nature [5, 37].

2.8.3 Wind Generation Control

The utilization of wind generation on the conventional power networks is widely spread in recent years. The rapid increase in such wind generation on power networks requires that it should assist in improving the control and stability of the conventional power system. As a matter of fact, system operators are imposing restrictions and control codes on wind farm connections to make sure the integrity of the power system is not compromised by the emerging wind generation. It is reported in the literature that power system stabilizers have been proposed for doubly-fed induction generator (DFIG)-based generation. Analysis and simulation results from the literature indicate that PSS installed on wind turbines can significantly contribute to the network damping. Furthermore, simulation results also demonstrate the superior capability of PSS on wind turbines in comparison to

the influence of PSS installed on local synchronous machines [38, 39]. This is quite promising and important especially when there is more wind generation.

2.9 Conclusion

Low frequency oscillations are inherent to interconnected power systems. There are various types of electro-mechanical oscillations the system exhibit; however, two common types are local and inter-area modes. To ensure power system dynamic stability and security and for maximum power transfer, these electro-mechanical oscillations must be mitigated through the use of supplementary damping controllers. Conventional power system stabilizers equipped to the automatic voltage regulators of synchronous generators are widely used to suppress oscillation modes. Speed-based PSS, frequency-based PSS, and power-based PSS are some common types of PSS. Of interest to the power system operators these days is the damping of inter-area oscillations which can cause power system outages and limit power transfer. The conventional power system stabilizers are quite effective in damping local modes and somewhat effective in damping inter-area. Therefore, compromise has to be made. Unfortunately, this might be at the cost of inter-area oscillation damping, thus, system stability.

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Chapter 3

Literature Overview of Supervisory Power System Stabilizers

3.1 Introduction

The issue of power system stability has been of a major concern since the early days of interconnecting the synchronous generators of different regions through high voltage transmission lines. The wide-spread problem of small-signal stability at the early stages is the loss of synchronism due to the lack of synchronizing torque. With the development of fast, automatic voltage regulators (AVRs) acting on the synchronous generators' excitation systems, this issue has been resolved by the increase of synchronizing torque, hence, ensuring the system will not lose synchronism. However, solving the problem of low synchronizing torque has come at the cost of deteriorating the damping of electromechanical oscillations of the weakly interconnected power system due to the negative damping characteristics of the AVRs [1]

To provide damping to ensure small-signal stability of the power system, decentralized power system stabilizers (PSSs) have been developed. The conventional power system stabilizers use local signals such as active power, rotor speed and/or frequency as input signals to provide a damping torque in phase with the speed deviation to damp local and inter-area oscillations. The PSSs are time-invariant controllers which are defined by transfer functions with constant parameters; the parameter of PSSs are determined using linearized plant model (i.e. synchronous generator connected to power

system) around a certain operating condition [2]. The distributed PSSs have proved to be good damping sources for local oscillations and to a certain extent for inter-area oscillations if the PSSs' parameters are designed for wide-range of operating conditions. However, PSSs along with other local controllers cannot guarantee the stability of the power system all the time if it is subjected to severe disturbances because of the non-linear and multivariable nature of the power system. Moreover, as a result of the deregulation of the power system, a heavy exchange of bulk power among the interconnected region over long distances causes an increase in the inter-area oscillations which cannot be effectively damped by local PSSs.

In recent years, the major concern of power system utilities has shifted towards inter-area oscillations rather than local oscillations because of the great impact inter-area oscillations can have on the power system as whole: the increase in inter-area oscillations can limit the amount of power exchange and can cause break-up of the whole power system if they cannot be damped effectively. And as stated previously, local PSSs are limited in damping inter-area oscillations due to the fact that these modes are not highly observable and controllable in local signals/states as the local oscillations. Also, it is possible that there is a strong coupling between local and inter-area oscillations; therefore, it is difficult to have local PSSs tuned to be as effective in damping inter-area oscillations as in the case of local oscillation damping. To gain knowledge of the nature of inter-area oscillations, the entire interconnected power system has to be represented in details as the inter-area oscillations are due to the dynamic interactions of the weakly coupled network; whereas, local oscillations are limited to their local regions only.

The great threat, caused by the presence of inter-area oscillations more than ever before due to the stressed operating conditions, has led engineers and researchers to look for improving the damping of inter-area oscillations. Investigations have shown [1-16] that using global signals fetched from different parts of the network and applied as inputs to new control schemes

can improve the damping of the inter-area oscillations, thus, increasing the security and reliability of the power system. With the advent of the new technology of phasor measurement units (PMUs), it has become possible to transmit wide-area dynamic information to the newly designed/proposed controllers.

This chapter will illustrate the different design methods used to develop supervisory power system stabilizers (SPSSs) using wide-area measurements to effectively damp inter-area oscillations.

3.2 Residue-Based Multi-Level PSS Design

In this control scheme [3], multi-level PSS using local and global signals are proposed. Each synchronous generator will be equipped with a conventional PSS to damp only local oscillations using a local signal (namely generator's rotor speed) and there will be another level of PSSs connected to selected machines in different regions through a coordinator using selected global signals. The second PSSs proposed are not centralized, but each one of them can be thought of as an individual SPSS acting on a selected generator.

First, the local and inter-area oscillations, right and left eigenvectors corresponding to the system eigenvalues λ_i are identified using Eigenanalysis on matrix A of the linear state space-model describing N -generator system:

$$\dot{x} = Ax + Bu = Ax + \sum_{j=1}^N B_j u_j \quad 3.1$$

Having identified the right and left eigenvalues, participation factors or transfer function residues are used to determine the best location of PSS. However, the emphasis is on using the residues method to determine the amount of phase lead required as well as the PSS parameters. The residue associated with i th mode and j th transfer function G_j of a machine is determined by:

$$R_{ij} = \lim_{s \rightarrow \lambda_j} (s - \lambda_i) G_j(s) \quad 3.2$$

where, G_j is the open-loop transfer function for a certain input/output of the j th generator. It is found that a controller at a machine j will be most effective in damping local or inter-area mode i if a proper input is chosen such that the residue R_{ij} will be maximum. In other words, the input signal with highest observability is the best candidate as an input for a controller. Adding the feedback controller to the machine with the maximum residue will shift the eigenvalue of the i -th mode to the left half complex plane (LHP). The way to shift the eigenvalue of the i th mode is to add a phase lead through the transfer function of a controller to compensate for the phase lag between excitation input and electric torque. The phase lead Φ_{ij} required, Figure 3.1, can be found by:

$$\phi_{ij} = 180^\circ - \arg(R_{ij}) \quad 3.3$$

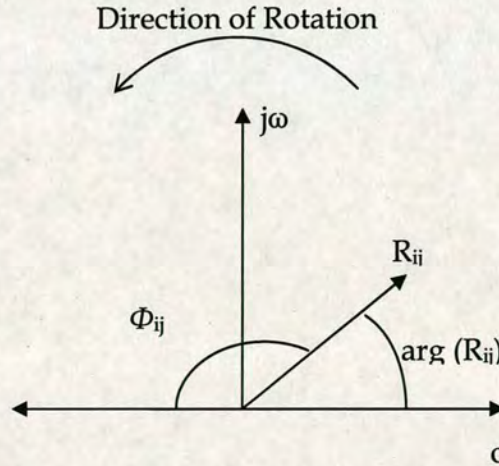


Figure 3.1 Amount of phase lead required [3]

It is found for inter-area oscillation damping, the proper controller's input signal with highest observability may not be in the same region where the second level PSS must be located. The design method of the multi-level controller is to provide a control signal or damping signal u_j which is the sum of two control signals from the multi-level PSS, as shown in Figure 3.2

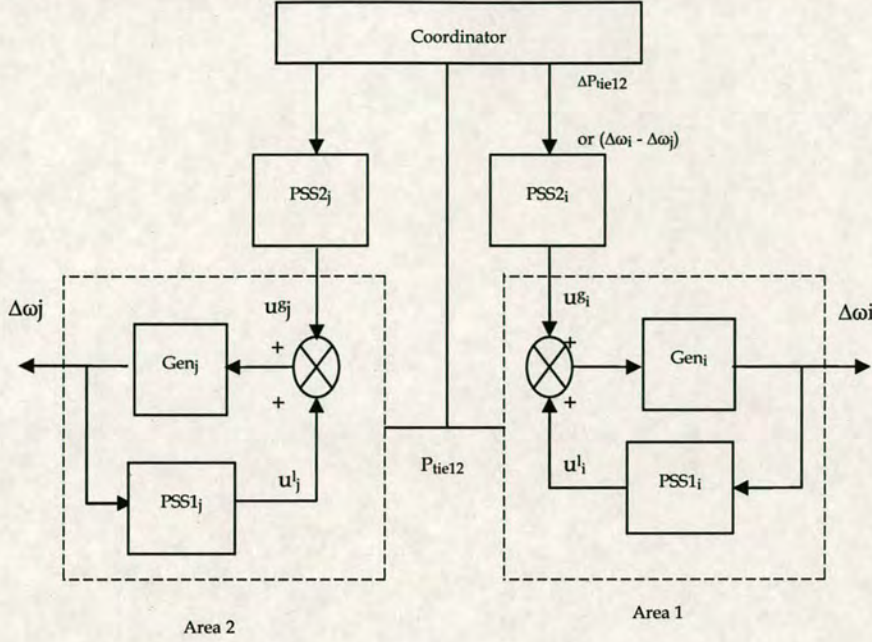


Figure 3.2 Two-level PSS design [3]

The first control signal u^l is to provide a local damping signal using generator rotor speed as an input signal to the local PSS since local generator rotor speed state always leads to maximum residue. This controller is called PSS1; it is the first level controller.

The second control signal u^s is to provide an inter-area damping using global signals which comprise of either tie-line active power or the difference of speed signal between two generators. This is the second level controller in the multi-level control design proposed. It should be noted that only selected machines will be equipped with second level PSS, so inter-area modes in one region could be controlled by machines from a different region. The total control signal/damping signal acting on the machine equals to

$$u_j = u_j^l + u_j^s \quad 3.4$$

The phase compensations for local and inter-area modes are computed at the local and inter-area mode frequencies, respectively. And the time constants for such controllers are determined accordingly in the usual manner from:

$$H_{pss}(s) = K \frac{sT}{1+sT} \left[\frac{1+sT1}{1+sT2} \right]^m \quad 3.5$$

where,

$$T2 = \frac{1}{\omega\sqrt{a}}, T1 = aT2, a = \frac{1 - \sin(\frac{\phi_{ij}}{m})}{1 + \sin(\frac{\phi_{ij}}{m})} \quad 3.6$$

T is wash-out time constant (usually 5-10 seconds),

ω is frequency of either local or inter-area mode in rad/sec,

Φ is the phase lag to be compensated

m is number of lead/lag stages required, and

K is PSS gain taken as one third of instability gain.

H_{PSS} is the lead/lag transfer function of each PSS to provide phase compensation required.

As mentioned previously, the global signals used are either tie-line active power or the difference in speed signal between two generators. The choice of such global signals can be justified as follows: Inter-area modes are very highly observable in the tie-line active power between areas causing such oscillations which explain why it is chosen as a stabilizing signal to damp inter-area modes associated with it. As for the second signal choice, it is observed that the observability that will lead to maximum residue for better inter-area damping (i.e. better performance by PSS2) can be obtained using the speed difference between the two machines rather than a speed signal from a single machine. This is because when using the speed deviation from generator j to control inter-area mode i , its corresponding residue R_{ij} might not be large enough to have adequate damping. To achieve a high residue magnitude, the observability and controllability of the modes of interest must be increased. But this increase especially controllability could be at the expense of the stability margin of local modes since the exciter forward gain is

increased to increase the residue R_{ij} corresponding to the speed deviation signal of generator j to control mode i .

The proposed two-level control design is one of the early attempts if not the first to use global signals to increase damping of inter-area modes and thus increase flexibility of power transfer between areas. It is simple to implement as it uses conventional PSS design method, and it does not require sophisticated algorithms or design methods. Although the controllers proved to be robust and provide satisfactory damping compared to using only local PSSs, the parameters of the second-level controller PSS2 are constants and cannot be modified online as new extreme conditions might destabilize the network.

3.3 H ∞ BASED SUPERVISORY POWER SYSTEM STABILIZER

With the advent of the H ∞ optimization method, an alternative control design technique has been proposed to design optimal controllers especially PSSs. The H ∞ method can lead to a robust controller to cover a wide range of operating conditions. In addition, the H ∞ method's ability to incorporate both classical and robust control concepts within a single design frame makes it appealing for the design of SPSS.

3.3.1 H ∞ -Fuzzy Logic Based SPSS

The proposed controller in paper [4] is robust and capable of compensating for the nonlinear dynamic operation and uncertain disturbances. Supervisory power system stabilizer makes use of remote (global) signals to increase damping of inter-area modes which cannot be effectively damped using local PSS (LPSS); thus, there will be a decentralized PSS equipped to each machine and centralized PSS, namely SPSS, acting on each region of the power system network.

The co-ordination between local PSSs and SPSS is through the use of the multi-agent system principle which is an active branch of distributed artificial intelligence. The multi-agent system theory is to employ a number of semi-autonomous agents to collaborate with each other to achieve a given task: in this case, there will be two agents namely the local agent, local PSSs, and a software agent, SPSS. The term agent implies that it learns from the environment.

The local conventional PSSs are designed to have fixed parameters determined by the usual methods which can be found in the literature [5]. But such design methods do not take into account the nonlinearity of the large-scale multivariable power system which is a major source of model uncertainty. By uncertainty, we mean (1) variations of linearized plant parameters as operating condition changes and (2) the inaccuracy of modeling transmission lines, transformers, and the loads.

The proposed SPSS control loop is a software agent that will have fuzzy logic controller switch whose function is to switch to the appropriate robust controller to provide a satisfactory damping. The controller embedded in the SPSS control loop will be designed based on H_∞ optimization method using selected wide-area measurements; the benefit of using H_∞ based controller is to take into account the nonlinear dynamic performance of the power system and model uncertainty unlike local PSS. The damping signals generated by the newly designed SPSSs act on the excitation systems of local machines to damp the system oscillations as shown in Figure 3.3.

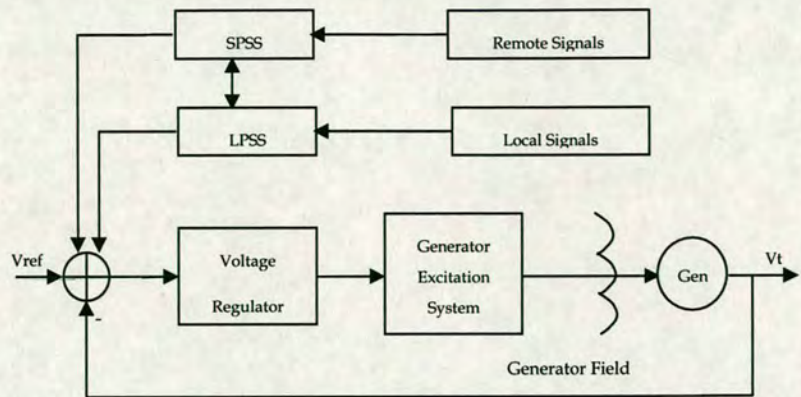


Figure 3.3 Conceptual input/output scheme of LPSS and SPSS [4]

In general, H^∞ control method is used to reject or minimize the closed-loop RMS gain from the disturbance input to the disturbance output of the closed-loop of the power system with H^∞ controller as a feedback, Figure 3.4. By minimizing the RMS gain, the effect of the disturbance input on the output of the power system will be reduced, thus, stabilizing the power system.

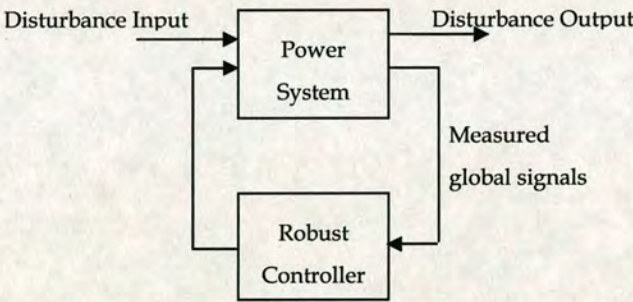


Figure 3.4 H^∞ control problem diagram [4]

The goal of the SPSS as stated previously is to damp inter-area oscillations; bearing this in mind, the inter-area dynamics must be extracted so that the signals in which inter-area modes are highly observable can be used as stabilizing signals for SPSS. Therefore, a parameter representing inter-area dynamics is introduced as

$$z = \text{constant} \tag{3.7}$$

The inter-area variable is a local variable associated with each region to which SPSS will be applied to. Since inter-area modes are very highly observable in tie-line active power exchanged over weak transmission lines, proposed inter-

area variable could be represented as the total real power generation of each region that is affected by SPSS. Other possible signals could also be frequency, accelerating power, and rotor speed. The choice of proper input signal to the robust controller SPSS (i.e. inter-area variable) depends on the observability analysis.

The next task as a part of the H_∞ optimization design method is to capture the uncertainty of the non-linear, time varying power system model. If $P(s)$ represents the open-loop transfer function linearized around a point, as the operating condition changes $P(s)$ might be a different linearized transfer function, namely $P'(s)$. Taking the difference between the two transfer functions represents the uncertainty of the unmodelled dynamics related to the nominal transfer function which a local PSS does not take into account. In mathematical formulation, $P'(s)$ can be represented as

$$P' = (1 + \Delta W(s)) P \quad 3.8$$

where,

P' is the transfer function of the perturbed plant,

P is the transfer function of the nominal plant,

W is the stable weighting function, and

Δ is the level of uncertainty.

The purpose of the weighting function is to measure the uncertainty variation with frequency.

To solve the H_∞ control problem, the linear matrix inequalities (LMI) approach is used with the wide-area measurements. To guarantee the existence of internally stabilizing controller, the condition $\gamma > 0$ must be met such that

$$\|F(G, K)\|_\infty < \gamma \quad 3.9$$

Where $\|F(G,K)\|_{\infty}$ is the closed-loop transfer function from the disturbance to the plant output, and γ is the prescribed H_{∞} performance value. Using the MATLAB LMI toolbox, the solution can be determined.

As stated previously, the co-ordination between LPSSs and SPSSs are through the multi-agent system theory. The SPSS agent consists of three main components: agent communications, fuzzy logic controller switch and H_{∞} based robust controller, Figure 3.5.

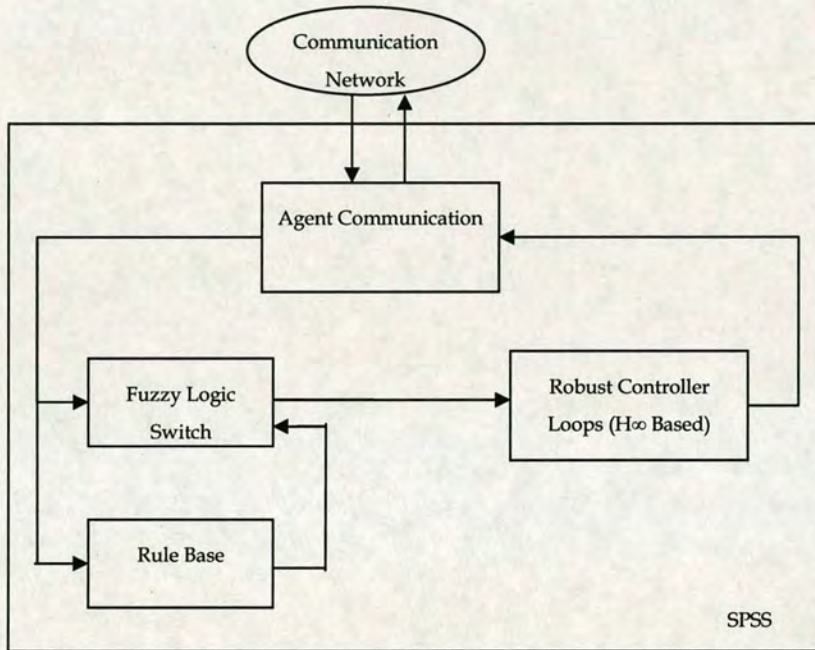


Figure 3.5 Aspect of the SPSS agent [4]

The communication agents will be used to transmit data with LPSS agents and other SPSS agents. Since communication devices are used to exchange data, time delay must be taken into account unless it is a very short time delay. A long time delay will have an adverse affect on the performance of the SPSS if it is not considered.

A Sugeno-type fuzzy interference [4] system (FIS) is used as fuzzy logic controller switch to select the appropriate action that the H_{∞} based robust controller must take after the operating conditions are identified by measuring the inter-area power flows for each region which the SPSS is acting upon. Therefore, the fuzzy based controlled switch and its rule base can be

considered the brain of the robust controller. The membership functions and other parameters of the FIS model (i.e. fuzzy logic switch) are tuned automatically by measurements through adaptive neuro-fuzzy learning techniques. Also, the SPSS agent has the ability to update the robust controller parameters, which happen in real time, for a new operating condition in the case where there is a deviation between the existing operating condition and the design system model. Therefore, the SPSS performance will be robust and satisfactory and the appropriate damping signal by SPSS will be sent to the machine(s) that will be most effective in damping the oscillation modes. These machines will be identified using the participation factor. Test results show the good performance of the proposed SPSS considering short time delays.

A drawback of the H_∞ based controller is that if the fuzzy logic switch makes the wrong selection of controller's loop (due to imperfect logic reasoning or inaccurate on-line measurements), the overall performance of SPSS can be compromised. The robust performance of pre-designed SPSS is also limited by the off-line system analysis, data gathering, and simulation modelling. Therefore, for better performance by SPSS, a complete and more accurate off-line study must be taken into account when designing the proposed SPSS.

3.3.2 H_∞ Damping Controller Design

Another approach [6] dealing with stability of large power system over a broad range of operating conditions or in the events of errors due to monitoring instruments is the design of a H_∞ damping controller. The first task in this study is to perform the modal analysis to obtain frequency, damping ratio and mode shape to identify which group of generators oscillate against another group of generators. A reduced model is obtained to replicate the real model for H_∞ based controller design. The reduced model must preserve the dynamic characteristics of the real model. Two methods are used to obtain such reduced models which are system identification method and coherency-based dynamic reduction method.

As stated before, the H_∞ problem is to reduce or minimize the effects of the disturbance on the output of the plant such that

$$\underset{\text{for all } \omega}{\text{Max}} |S(j\omega)| \leq |W_1^{-1}(j\omega)| \quad 3.10$$

where $S(j\omega)$ is the closed-loop transfer function from disturbance to the plant output, and $W_1(j\omega)$ represents the acceptable performance magnitude of error in the presence of disturbances. To accommodate for the nominal plant's additive and multiplicative uncertainties, $\Delta_A(s)$ and $\Delta_M(s)$ respectively, in the H_∞ problem, the following criteria is added:

$$\begin{aligned} \text{Max} |R(j\omega)| &\leq |\Delta_A(j\omega)| = |W_2^{-1}(j\omega)| \\ \text{Max} |T(j\omega)| &\leq |\Delta_M(j\omega)| = |W_3^{-1}(j\omega)|, \text{ for all } \omega \end{aligned} \quad 3.11$$

where $R(j\omega)$ and $T(j\omega)$ are the transfer functions of the perturbed plant with controller shown in [6]. The H_∞ algorithm will provide an optimal controller whose performance must meet the following criteria simultaneously:

$$\left\| \begin{bmatrix} W_1(j\omega)S(j\omega) \\ W_2(j\omega)R(j\omega) \\ W_3(j\omega)T(j\omega) \end{bmatrix} \right\|_\infty \leq 1 \quad 3.12$$

where $\| \cdot \|_\infty$ represents the maximum magnitude of the vector over all frequencies, ω . For the solution of the H_∞ problem, two Riccati equations are solved. Further details about the solution process can be found in the literature [7, 8]. The weighting functions, W , have a great impact in obtaining the optimal parameters of the controller that will meet the specification requirements.

Most of the studies that propose supervisory power system stabilizer design either assume no time delays or short time delays which can be negligible. Such assumptions could have detrimental consequences on the overall response of the SPSS. Since long time delays (if not taken into consideration) will result in phase lag with respect of frequency of oscillatory mode instead of compensating for the phase lag and could also result in gain amplification

with respect of oscillatory mode damping. The net consequence is to shift the eigenvalues of the oscillatory modes to undesirable places on the complex plane, and that could result in destabilizing the power system instead of stabilizing it [9]. Therefore, the next proposed H_∞ based SPSS takes into account delayed-input wide area measurements by using the Gain Scheduling Method [10].

The linear matrix inequality (LMI) H_∞ method is used to design the SPSS as previously studied. Speed deviations from the local generators are measured and used as inputs to the SPSS. The gain scheduling (GS) method (rather than the general linear fractional transformation (LFT)) is used to accommodate time delays because LFT leads to conservative results. With the GS method, the parameters of the controller are measured in real time; therefore, GS-based controller is of a dynamic nature rather than fixed. Moreover, the proposed GS design method will lead to linear time-invariant controller for each operating condition and will ensure smooth controlling switching as the operating condition changes. System plant is expressed as

$$\begin{aligned}\dot{x} &= A(q)x + B_1(q)w + B_2u \\ z &= C_1(q)x + D_{11}(q)w + D_{12}u \\ y &= C_2x + D_{21}w + D_{22}u\end{aligned}\tag{3.13}$$

To design H_∞ parameter-dependent controller using GS, the controller must be expressed as

$$\begin{aligned}\dot{x}_k &= A_k(q)x + B_k(q)u \\ y_k &= C_k(q)x + D_k(q)u\end{aligned}\tag{3.14}$$

where the values of $A_k(q)$, $B_k(q)$, $C_k(q)$, and $D_k(q)$ can be determined as

$$\begin{pmatrix} A_k(q) & B_k(q) \\ C_k(q) & D_k(q) \end{pmatrix} = \sum_{i=1}^n \alpha_i \begin{pmatrix} A_{kqi} & B_{kqi} \\ C_{kqi} & D_{kqi} \end{pmatrix}\tag{3.15}$$

where α is

$$q = \sum_{i=1}^n \alpha_i q_i\tag{3.16}$$

The controller state-space can be determined by the convex interpolation of the LTI vertex controllers at the operating point q :

$$\begin{pmatrix} A_{kqi} & B_{kqi} \\ C_{kqi} & D_{kqi} \end{pmatrix} \quad 3.17$$

This results in robust, smooth switching controller by the parameter measurements q which can be an index of operating conditions or a signal of interest. This method can be used to design a stabilizing controller for a system

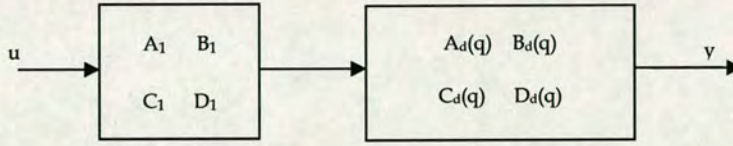


Figure 3.6 Delayed-system without controller [6]

with time delay, Figure 3.6. If the time delay is approximated by the first order Pade approximation [11], it can be represented as:

$$\begin{aligned} \dot{x} &= -\frac{2}{\tau_d}x + \frac{4}{\tau_d}u \\ y &= x - u \end{aligned} \quad 3.18$$

$1/\tau_d$ is replaced by q , then

$$\begin{aligned} A_d(q) &= -2q & B_d(q) &= 4q \\ C_d(q) &= 1 & D_d(q) &= -1 \end{aligned} \quad 3.19$$

After connecting the system plant model and the time delay model, the LMI H_∞ controller design can be applied to the delayed-input system plant, Figure 3.7, to yield robust, linear time-invariant for each operating condition, and the controller's parameters are measured in real time as previously stated. It should be noted that the local PSSs are removed from the study model when the SPSS is tested.

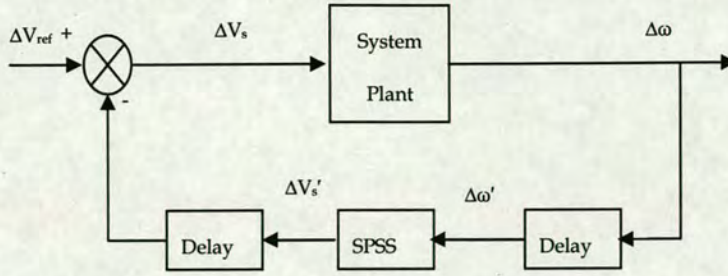


Figure 3.7 SPSS Controller [6]

3.4 Decentralized/Hierarchical Approach

A sequential optimization procedure is used to tune the parameters of the proposed controller which is improving the conventional PSS using remote signals [12]. The proposed approach is to have two-level control loops: speed-based local PSS for damping local oscillation modes, and a global PSS based on the differential frequency between two suitably selected remote areas. The global information or wide-area measurements sent by phasor measurement units shows the network dynamic information that cannot be revealed by local signals, thus, inter-area oscillations can be observed and controlled better with global signals than with local signals.

The second control loop is not a centralized control strategy *per se* as not every measurement is sent back to every controller. This is because only a few control sites, (which can provide controllability over some specific modes of interest under specific pre-determined network configurations), are equipped with second level of PSSs. Therefore, not every control site must be involved.

The first step toward the design of PSS is to identify the model of the studied system which can be explicitly written in state-space MIMO equations.

$$\begin{aligned}\dot{x}(t) &= Ax(t) + Bu(t) \\ y &= Cx(t)\end{aligned}\tag{3.20}$$

where,

x is the state vector,

$u(t)$ is the input vector, and

$y(t)$ is the measured output vector;

A , B , and C are state, input, and output matrices, respectively.

And then the system dynamic interactions are analyzed by using eigenvalue and singular value analyses. Geometric measures introduced by Hamdan [12] are used to study the strength of a signal or controller's performance in a given mode of interest (i.e. to assess the modal controllability and observability to determine the proper input-output pairing signals for efficient satisfactory damping).

Once the eigenvalues and corresponding right- and left-eigenvalues are identified through the system matrix A of the state-space form, the geometric measures of controllability and observability associated with the mode k are determined by:

$$m_{ci}(k) = \cos(\alpha(f_k, b_i)) = \frac{|b_i^T f_k|}{\|f_k\| \|b_i\|}$$

$$m_{oj}(k) = \cos(\theta(e_k, c_j^T)) = \frac{|b_j e_k|}{\|c_j\| \|e_k\|} \quad 3.21$$

where,

f and e correspond to the k th mode of the right and left-eigenvectors,

b_i is i th column of B corresponding to the i th input, and

c_j is the j th row of C corresponding to the j th output.

These equations imply that if the $m_{ci} = 0$, then the k th mode is uncontrollable from input i . If $m_{oj} = 0$, then the k th mode is not observable from the output j . The residue method which was explained previously can also be used to identify the modal controllability/observability. Unfortunately, the residue method suffers from a scaling problem if the output matrix C involves different physical signals such as tie-line power flow, bus frequency, shaft-speed, angle shift, etc, and its accuracy is guaranteed only when all the

outputs are of the same type. On the other hand, the geometric measures can be effective even for inputs and outputs of different types.

The Singular Value Decomposition of transfer function

$$Y(s) = \Phi(s)U(s) \quad 3.22$$

where,

Y is the output vector

U is the input vector, and

Φ is the transfer function.

is sometimes used instead of the geometric measure if the controller is to be robust for wide-range frequency. The reason is that when trying to assess the controllability and observability of a system at forced sinusoidal excitation frequencies located on the imaginary axis to ensure robust controller design, the geometric measures fail to show in theory the controller interactions at non-natural oscillatory modes. Once a thorough system analysis is performed to study the dynamic interactions, the control sites to which the multi-level PSS is applied are identified. The sum of the two PSS signals is applied to machine voltage reference. Tuning of the multi-level PSS is performed according to the sequential procedure by tuning first the local loops then global loop to provide a satisfactory damping performance. The last optional stage is to co-ordinate between the two loops to enhance their overall effects to make use of the global strategy.

Each stage of the global loop is a differential filter represented by

$$F(s) = K[K_A F_A(s) - K_B F_B(s)] \quad 3.23$$

Where F_x is a rational fraction defined by

$$F_x(s) = \left(\frac{1 + sT_1^x}{1 + sT_2^x} \right) \left(\frac{1 + sT_3^x}{1 + sT_4^x} \right) \left(\frac{1 + sT_5^x}{1 + sT_6^x} \right),$$

$$(X = A, B) \quad 3.24$$

Where F_x and K represent various time constants and gains of the global PSS. To tune the PSS, the various time constants and gains in each differential filter must be assigned adequate values based on a genetic optimization or constrained nonlinear optimization procedure which can be formulated as:

$$\min_{p=\{T_i^x, K_i\}} J(p) \text{ s.t. } \max\{\Re(\lambda_k)\} < 0, \quad k = 1, 2, \dots, n \quad 3.25$$

where p is the PSS parameter vector and J is user specified cost function to assess the overall damping performance of closed-loop system. J represents the energy contained within the damped signal response of the closed-loop system; in other words, large J corresponds to poor damping performance of the closed-loop system and vice versa.

As with other control loop using wide-area measurements, long time delays will have a detrimental effect on the overall damping performance of the decentralized/hierarchical approach. On the other hand, the loss of global signals will not have a severe consequence on the damping performance as in the case of the centralized controllers [12].

Another approach based on hierarchical controller (i.e. global controller) to stabilize large power system using wide-area measurement is found in the literature [13]. With the proposed controller, the large power system becomes stable under severe conditions. The proposed solution is a two-level controller: a local controller equipped to each generator using local signals to damp local oscillations and helped by multi-variable central global controller at the secondary level to damp inter-area oscillations. It is a multi-variable global controller because the remote signals are from all generators, and they are generator's terminal voltage, power angle, and rotor speed. By using the wide-area measurements, the global controller synthesize two outputs to decouple the subsystems' dynamics, thus, improving the performance of the local controller (i.e. it decouples each generator's dynamics from the other generators).

The local controllers, by themselves, produce a conservative performance in dealing with the remote interactions among generators because they are governed by local control laws (i.e. they use local signals to control remote interactions). In addition, they are single-input-single output (SISO) and do not take into account the non-linear nature of the power system. On the other hand, the proposed global controller compared to the previous global controllers illustrated so far takes into account the remote interactions and the multi-variable and non-linear nature of the large power system according to the authors. Also, the voltage profile and rotor oscillation damping problems are taken into account simultaneously. The drawback with such global controllers is the requirements of telecommunication equipment to transmit the global signals to the central controller. However, the proposed global controller's performance is considered satisfactory up to a fixed time delay of 10 milliseconds. A condition stipulated on the design process of the global controller is that its stabilizing signals must be equal to zero in the case of steady-state. In other words, it must contribute nothing when there is no disturbance at all.

By large power systems, it means several generators that provide active and reactive powers through transmission lines and transformers. To obtain the overall model of the power system, its components' models are aggregated: synchronous generators are represented by their different non-linear equations, and loads, lines, and transformers are represented by constant impedance.

The design process of the secondary-level controller using wide-area measurements is based on the reformulation of the multimachine power system model to have generators' terminal voltages represented as state variables in the new power system model. Thus, first synchronous generator, exciter, and prime mover models are defined and can be found in [14]. As it is adopted in the literature [15], for stability study and controller design, various simplified models are used such as third-order and forth-order synchronous

generator model. The third order synchronous generator model known as two-axis model is used in this study. Figure 3.8 describes the generator's components. The limitations imposed on the excitation system and the valve inputs are considered during the simulation process.

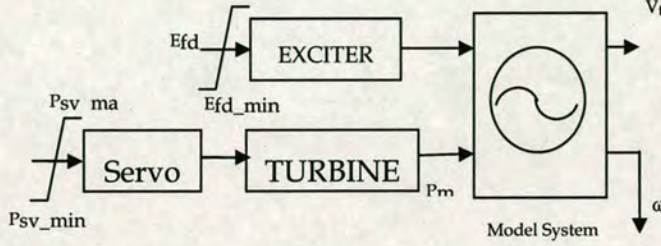


Figure 3.8 Generator's components [13]

The equations describing the above models represent the multi-machine model used in [15]. The multi-machine model depends on variables which are not state variables, so it renders inappropriate for control design scheme. So the aim is to obtain dynamic equations of the multi-machine model free of voltages and currents at a bus without generator. The generators' terminal voltages are used as state variables instead of internal field voltage and winding flux linkages which are not easily measured. The new model equations can be found in [13].

Having established the dynamic equations, the global control laws for each subsystem which consist of a generator and its local controller are derived. As stated previously, the aim is to have the global controller compensate for the remote interactions among generators to improve the local controller's performance and to improve damping of inter-area oscillations. Since the proposed controller should have no contribution when the power system is in steady-state, a change of variable must be performed again on the previously obtained multimachine model to ensure its action is zero at steady-state.

$$e_{1i} = v_{di} - V_i^{ref} \sin(\delta_i - \theta_i^{ref}) \quad 3.26$$

$$e_{2i} = v_{qi} - V_i^{ref} \cos(\delta_i - \theta_i^{ref}) \quad 3.27$$

$$e_{3i} = \omega_i - \omega_s \quad 3.28$$

where,

v_d and v_q are voltage of generator in the d-q reference frame,

ω_s and ω_i are synchronous and rotor speed respectively, and

$V_i^{ref}, \theta_i^{ref}$ are the terminal voltage reference and generator local d-q reference frame position in the absolute reference frame.

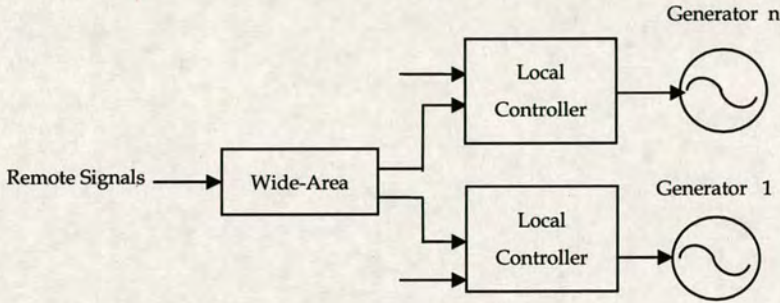


Figure 3.9 Hierarchical control scheme [13]

The new dynamic equations in the new coordinate after substituting the above equations are equations 17-21 in [13]. The hierarchical controller is composed of two control signals: the first one is the output of the local controller and the second control signal is the output of the global controller, Figure 3.9. In mathematical form, the total stabilizing signals are:

$$e_{fdi} = e_{fdi}^l + e_{fdi}^g \quad 3.29$$

$$P_{svi} = P_{svi}^l + P_{svi}^g \quad 3.30$$

e_{fdi} and P_{svi} are the stabilizing signals acting on the excitation and governor respectively. After few manipulations, the global control laws for generator i can be obtained as

$$e_{fdi}^g = \frac{-(\psi_{e1}^i e_{1i} + \psi_{e2}^i e_{2i})}{\rho_{1i} e_{1i} + \rho_{2i} e_{2i}}, \text{ if } \rho_{1i} e_{1i} + \rho_{2i} e_{2i} \neq 0 \quad 3.31$$

$$P_{svi}^g = \frac{T_{rH}}{A_i} \dot{\psi}_{\omega i}^g \quad 3.32$$

where the components in the above expressions can be calculated using the equations in [13]. A scaling again γ_i , which ranges between 0 to 1, is added to the global control laws to avoid saturation of the excitation and the valve input during severe conditions such as short circuit at a generator bus. The global equations become:

$$e_{fdi}^s = \gamma_i \frac{-(\psi_{e1}^i e_{1i} + \psi_{e2}^i e_{2i})}{\rho_{1i} e_{1i} + \rho_{2i} e_{2i}}, \text{ if } \rho_{1i} e_{1i} + \rho_{2i} e_{2i} \neq 0 \quad 3.33$$

$$P_{svi}^s = \gamma_i \frac{T_{rH}}{A_i} \dot{\psi}_{\alpha}^s \quad 3.34$$

A drawback of the two-level hierarchical controller is that it performs well as long as the time delay does not exceed 10 milliseconds as stated previously. An improvement to this proposed hierarchical controller is introduced to design a robust, insensitive two-level hierarchical controller since long time delays can sometimes reduce considerably the performance of global signals based controller. By using a Smith prediction approach, the performance of the previously proposed two-level hierarchical controller is preserved when there are detrimental long time delays in transmitting global measurements and communication delays between the central and local controllers. In addition, the Smith approach enhances the robustness and insensitivity of the hierarchical controller to the nonlinear dynamic behaviour of different power system loads by an online load estimation algorithm to continuously update both the central controller and predictor parameters [14].

The power system model and network equations used for the improvement process are the same as in [13]. As previous study, the control signals consist of two stabilizing signals: one corresponds to the output of the local controller, and the second signal corresponds to the output of the global signal but in this case time delays are taken into consideration:

$$e_{fdi}(t) = e_{fdi}^l(t) + e_{fdi}^s(t - D_{li}) \quad 3.35$$

$$P_{svi}(t) = P_{svi}^l(t) + P_{svi}^s(t - D_{li}) \quad 3.36$$

where,

e_{fdi} is field voltage of generator i ,

P_{svi} is steam valve position, and

D_{1i} is the communication delay between wide-area controller and the local controller of generator i .

The global terms of e_{fdi} and P_{svi} are derived such that the interaction terms in the voltage and rotor speed are cancelled by adopting the linearization design method which yields the following global terms:

$$e_{fdi}^g(t - D_{1i} - D_{2i}) = -\frac{(\psi_{e1}^i(t - D_{2i})e_{1i}(t - D_{2i}) + \psi_{e2}^i(t - D_{2i})e_{2i}(t - D_{2i}))}{\rho_{1i}e_{1i}(t - D_{1i}) + \rho_{2i}e_{2i}(t - D_{1i})}$$

if $\rho_{1i}e_{1i} + \rho_{2i}e_{2i} \neq 0$ 3.37

$$P_{svi}^g(t - D_{1i} - D_{2i}) = \frac{T_{CHi}}{K_{HP}} \dot{\psi}_{\omega i}^g(t - D_{2i})$$

3.38

where,

D_{2i} is the measurement delay between generator i and wide-area controller.

Rewritting the expressions at the instant t , they yield:

$$e_{fdi}^g(t) = -\frac{(\psi_{e1}^i(t + D_{1i})e_{1i}(t + D_{1i}) + \psi_{e2}^i(t + D_{1i})e_{2i}(t + D_{1i}))}{\rho_{1i}e_{1i}(t - D_{1i}) + \rho_{2i}e_{2i}(t - D_{1i})}$$

if $\rho_{1i}e_{1i} + \rho_{2i}e_{2i} \neq 0$ 3.39

$$P_{svi}^g(t) = \frac{T_{CHi}}{K_{HP}} \dot{\psi}_{\omega i}^g(t + D_{1i})$$

3.40

The expressions of the parameters appearing in the above equations can be found in [14]. A scaling gain ranging from 0 to 1 is added to the global expressions to cope with modelling approximation and practical limitation on control inputs:

$$e_{fdi}^g = -\gamma_i \frac{\psi_{e1}^i e_{1i} + \psi_{e2}^i e_{2i}}{\rho_{1i} e_{1i} + \rho_{2i} e_{2i}} \quad |e_{fdi}^g| \leq e_{fdi_max}^g$$

3.41

$$P_{svi}^g = \gamma_i \frac{T_{CHi}}{K_{HP}} \dot{\psi}_{\alpha i}^g \quad \left| P_{svi}^g \right| \leq P_{svi_max}^g \quad 3.42$$

The scaling gain γ is weighting factor tuned by the designer to determine the level of contribution of the global controller signal especially in the case of severe contingencies. The Smith prediction methodology is used to cancel the delayed output of the plant by producing a signal similar to the plant output. The delay-free system model is also introduced to the controller to predict the measurements. Therefore, the quality of predictions depends on the accuracy of the approximation of the plant and local control of the system model. Compared to the hierarchical based controller limited to the 10 millisecond time delay, test results show the improved controller is robust and insensitive to relatively long time delays.

Figure 3.10 illustrates the interaction between the global signals and the local AVR-PSS/Governor.

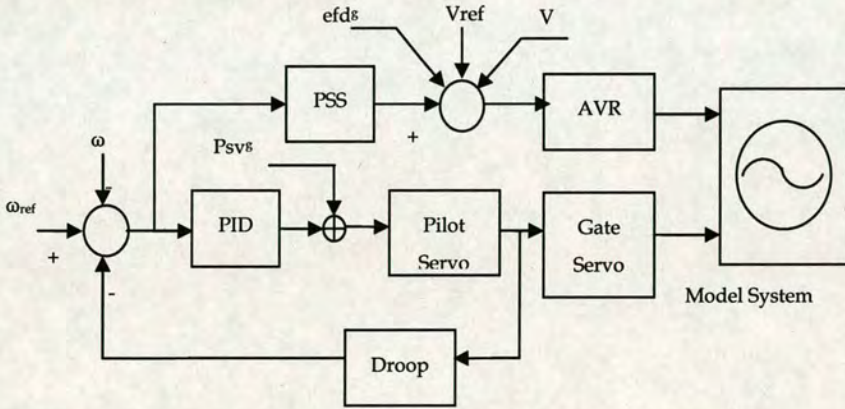


Figure 3.10 Local controller with global signal from the central controller [14]

3.5 SLIDING-MODE BASED SUPERVISORY POWER SYSTEM Stabilizer

A Nonlinear supervisory power system stabilizer can also be used to augment fuzzy-logic-based local power system stabilizer when there is a possibility that the stability of power system is about to be lost.

Generally, it is hard to achieve a closed-loop optimal control for a power system due to its non-linearity and complex nature. And in order to have an effective control scheme, it has to be adaptive and nonlinear. In the proposed design process, a new nonlinear design local expert controller based on the concept of a fuzzy linguistic control is proposed and equipped to each machine in a multimachine network.[16] shows that the proposed local fuzzy-based PSS performs well enough as long as the its parameters are suitably determined. Nevertheless, if the transient disturbances are severe and cause the stability of the system to be lost, robust nonlinear SPSS based on sliding-mode control concept will take action to preserve the stability of the power system. The SPSS takes action only if the system output error is large during severe transient disturbances. Thus, the stabilizing signal consists of two signals namely u_c from the local fuzzy-based controller for normal disturbances and u_s from sliding-mode based SPSS during severe disturbance which results in an increase of output errors beyond a certain limit that might cause the loss of stability.

To design SPSS based on sliding mode control concept, each synchronous generator in the multimachine power system is represented by 5th order model. For SPSS design, a switching hyperplane is chosen such that

$$s = c_1\omega + \dot{\omega} \quad 3.43$$

where,

- c_1 is a parameter > 0
- ω is generator speed, and
- $\dot{\omega}$ is speed acceleration.

Taking the derivative of s and substitute for $\dot{\omega}$ yields

$$\dot{s} = c_1\dot{\omega} + f(x) + bu \quad 3.44$$

where,

$f(x)$ and b are equations derived from the power system model found in [16], and

u is the stabilizing signal consisting of u_c and u_s (i.e. $u = u_c + u_s$).

to satisfy the condition $|s| < \varepsilon$ which defines when the fuzzy-logic controller will operate, the value of u_s is chosen as

$$u_s = -\frac{f_M}{b} \text{sgn}(s) \text{ for } |s| > \varepsilon \quad 3.45$$

where,

$$f_M \geq |f^u(x)| + |b^u u_c| + c_1 |\dot{\omega}| \quad 3.46$$

where,

ε is the width of boundary layer and small,

$f^u(x)$ is the upper limit of $f(x)$, and

b^u is the upper limit of b .

Again, to satisfy the condition $|s| < \varepsilon$, the value of u_s must be as

$$u_s = -\frac{f_M s}{b^L \varepsilon} \text{ for } |s| < \varepsilon \quad 3.47$$

where,

b^L is the lower limit of the control gain b .

With such conditions, the supervisory controller signal u_s will lead to a saturation control and reduction of the control gain acting on the switched control signal bounded by the switching line region to ensure that the high-gain control caused by SPSS can only take place if the output error exceeds the set limits. Figure 3.11 shows the overall proposed controller structure for a multimachine power system.

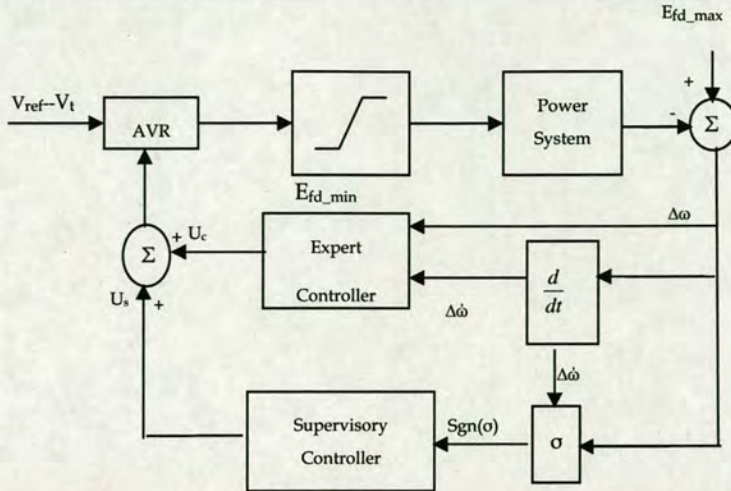


Figure 3.11 Block diagram supervisory control of a power system [16]

3.6 Conclusion

Local power system stabilizers cannot guarantee stability of the power system if it is subject to very high inter-area oscillations which are expected to happen because of the bulk power exchange between different weakly interconnected regions (especially after the deregulation of the power system, increase load demands and the stagnant expansion of the transmission lines). In addition, LPSS is designed based on local control laws, whereas, the inter-area oscillations are due to the dynamic interactions of machines in different regions. Thus, wide-area measurements could be nominated as remote input signals to enhance damping of inter-area oscillations, and with the development of phasor measurements units, it is easy to transmit data as input signals to a newly designed supervisory power system stabilizer to damp inter-area oscillations. The literature shows that there are various kinds of proposed SPSS based on for example H_∞ or sliding-mode control concepts. Test results show a major improvement in the stability of power system using wide-area measurements as input signals to SPSS. However, care must be taken when designing such global controllers when it comes to time delays, as long time delays not considered in the design process could have a detrimental effect on the stability of power system.

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Chapter 4

Fuzzy Logic Review

4.1 Introduction

FUZZY set theory was first introduced on a paper “Fuzzy Sets” written by Prof. L. A. Zadeh, University of California Berkeley, U.S., in 1965. Prof. Zadeh defined fuzzy sets as sets that contain vague or ambiguous information or hold partial truth. Hence, its boundaries are ambiguously defined unlike classical sets whose elements have crisp boundaries and either belong or not to a classical set. This is based on the accuracy or imprecision of the information it is available. To use classical methods, the accuracy and imprecision of information are transformed into restrictions under which mathematical formulations of solving real-world problems are derived, and this can lead to conservative solutions. Therefore, it is preferable to take in to account and have means to represent the uncertainties or imprecise information about a particular engineering or scientific problem.

With the advent of fuzzy logic (which is an extension of fuzzy set theory), the fuzziness and uncertainties associated with complex problems can be represented in humanistic system or natural language as will be illustrated later on [1]. In addition, compared with the classical solutions that require mathematical details of the plant to design controllers, fuzzy set theory or fuzzy logic can be used to design controllers for ill defined systems or systems with uncertainties without the need for the exact mathematical representation of the plant model. So fuzzy logic provides a different means of thinking to model complex systems based on a higher level of abstraction and past experience and knowledge accumulated previously [2]. So the main benefit of fuzzy logic technology is its ability for approximate reasoning of system

behaviour whose numerical solutions (as well as analytic functions) do not exist.

In approximate reasoning, fuzzy systems attempt to produce optimal solutions based on its inference of the specific from the general. This is also called deductive reasoning. Having stated some of the benefits of fuzzy logic technology, it is not surprising why it is becoming the most popular approach in developing solutions of today's complex problems [3].

In the first part, fundamental concepts of fuzzy set theories and fuzzy logic are illustrated. Then, fuzzy logic applications in power systems especially in developing power systems stabilizers will also be discussed briefly.

4.2 Basic Concepts of Fuzzy Set Theory

4.2.1 Classical Sets and Fuzzy Sets

In classical or crisp set, an element x in the universe of discourse X can either belong or not to a classical set A defined on X (i.e. sub-set of X): an element x is either absolutely a member or not in a crisp set A . In a mathematical form, the membership of element x in classical set A can be represented by an indicator function as:

$$\mu_A(x) = \begin{cases} 1; & x \in A \\ 0; & x \notin A \end{cases} \quad 4.1$$

μ_A indicates the degree of membership of an element x in this case in the classical set A . As it is clearly shown from equation 4.1, if the element x belongs to set A , its grade of membership in a classical set A is 1.0; otherwise, 0.0.

When there are uncertainties in problems, the first important step in decision making is to represent the fuzziness in fuzzy sets on a universe of discourse, again let us say X . In a fuzzy set A defined on the universe of discourse X , the

degree of membership value of the element x can be between the range of the unit interval $[0,1]$ and defined mathematically as follows:

$$\mu_A(x) \in [0,1] \quad 4.2$$

This mathematical form of representing fuzzy set A indicates that each fuzzy set is a function that maps objects of universe X onto the unit interval $[0,1]$. And membership function μ_A can be considered as a measure of the membership degree to which element x belongs to fuzzy set A [1].

From the above definitions, the main difference between classical sets and fuzzy sets is their membership values: the classical or crisp sets have unique membership values that are either 1.0 or 0.0. Whereas, in fuzzy sets the uniqueness is replaced by flexibility because the membership values can be anywhere between $[0,1]$ and can be adjusted to suit a particular situation. So clearly, classical sets have a sharp, unambiguous boundary; whereas, fuzzy sets have fuzzy boundaries. In terms of membership values in fuzzy set A , the closer the value of μ_A to 1.0, the more x belongs to fuzzy set A : when μ_A is equal to 1.0, it indicates that element x has a full or complete membership in fuzzy set A , and when μ_A is equal to 0.0, it means element x has null membership in fuzzy set A , Fig. 4.1.

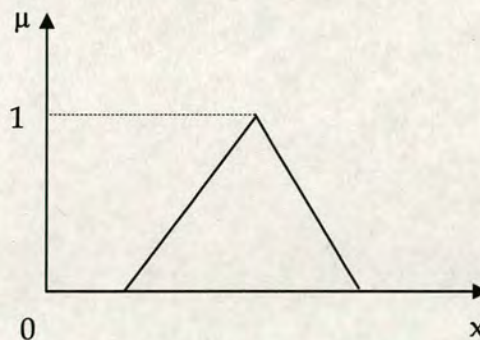


Figure 4.1 Typical membership function of fuzzy set [1]

4.2.2 Fuzzy Set Operations

Fuzzy sets contain elements of various degrees of membership values on the range $[0,1]$ as stated previously. Since the membership value of element x can take any value in this range, an element that belongs to one fuzzy set can also belong to other fuzzy sets on the universe of discourse X as long as the value of μ_A is not complete ($\mu_A < 1$). And the sum of the membership values of element x that belongs to different fuzzy sets on the same universe of discourse should not exceed 1.0 as the maximum range on the unit interval is 1.0, Fig. 4.2.

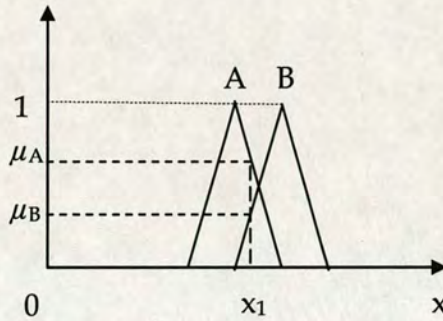


Figure 4.2 Element x_1 in two fuzzy sets [1]

This is important when it comes to performing function-theoretic operations on fuzzy sets, say A and B . The most commonly used fuzzy set operations are union, intersection, and complement operations and are defined respectively as:

$$\text{Union} \quad \mu_{A \cup B}(x) = \max[\mu_A(x), \mu_B(x)] \quad 4.3$$

$$\text{Intersection} \quad \mu_{A \cap B}(x) = \min[\mu_A(x), \mu_B(x)] \quad 4.4$$

$$\text{Complement} \quad \mu_{\bar{A}}(x) = 1 - \mu_A(x) \quad 4.5$$

De Morgan's principle and other operators such as commutativity and associativity for classical sets can also be applied for fuzzy sets except for the excluded middle axioms.

An important concept in fuzzy logic operations is fuzzy relation. A fuzzy relation maps elements in fuzzy sets of different universes of discourse to each other through the Cartesian product of the two universes. That is to say every element in universe X has a relationship to every element in universe Y if we are to map elements in X to elements in Y . And the strength of such pairing between elements is measured by the membership function defined on the unit interval $[0,1]$ and expressed as $\mu_R(x,y)$ where R is the matrix relation between X and Y . Fuzzy relation can be defined through the Cartesian product space as:

$$A \times B = R \subset X \times Y \quad 4.6$$

and the membership function of the fuzzy relation R can be expressed as:

$$\mu_R(x, y) = \mu_{A \times B}(x, y) = \min(\mu_A(x), \mu_B(y)) \quad 4.7$$

As with crisp relations, fuzzy composition can also be applied to different fuzzy relations to relate elements in these fuzzy relations. If for example, fuzzy relation R is defined on Cartesian space $X \times Y$ and S is a fuzzy relation on the Cartesian space $Y \times Z$, by using the fuzzy max-min composition or max-dot composition, we can find relation T whose elements belong to universe X and universe Z . The composition matrix T , the max-min composition membership function, and max-product membership function are defined respectively as follows:

$$T = R \circ S \quad 4.8$$

$$\mu_T(x, z) = \max_{y \in Y} (\min(\mu_R(x, y), \mu_S(y, z))) \quad 4.9$$

$$\mu_T(x, z) = \max_{y \in Y} (\mu_R(x, y) \bullet \mu_S(y, z)) \quad 4.10$$

It should be pointed out that there are other sets of operations that can be performed on fuzzy sets, but the most important operations are illustrated.

4.2.3 Membership Function Properties

As stated previously, power of fuzzy logic is that it does not require deep understanding of the mathematical behaviour of the system to which the fuzzy system will be applied. However, as a first step towards the solution of a complex system, the fuzziness and vagueness must be characterized, and the membership functions that characterize such fuzziness in fuzzy sets are usually depicted graphically so that they can be used later on to form the mathematical basis on which fuzzy set theory is applied. The shapes of the graphically depicted membership functions can be of different kinds, and there are no restrictions or limitations imposed on the shapes. But the most popular forms of membership function are the ones that are normal and convex, Fig. 4.1. So clearly, it is very important to understand how to describe and develop the membership functions as its description forms the basis of a fuzzy operation.

There are different ways that the literature shows to develop membership functions and assign membership values to fuzzy variables; some of these ways are intuition, inference, neural networks, genetic algorithms, and the last but not the least inductive reasoning. Such process of converting crisp quantities to fuzzy quantities is called fuzzification. The fuzzification will assign values in the range of the unit interval $[0,1]$ to fuzzy variables. Fig 4.3 shows an example of membership functions corresponding to different types of fuzzy variables (i.e. cold, cool, warm, and hot) on the universe of temperature measured in units of degrees Celsius [1].

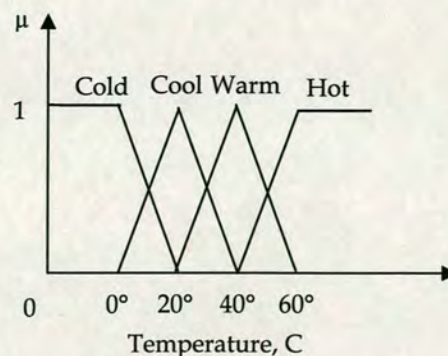


Figure 4.3 Membership functions for fuzzy variable temperature

Each curve representing a membership function is labelled to be used when the fuzzy system is implemented using rule-based system as it will be explained later. Although the membership functions can take various forms of shapes, the shapes of these curves are not as important as the following few characteristics which play important roles in the development of a fuzzy system:

1. The number of partitions/curves used to divide the universe of discourse.
2. The positions of the curves on the universe of discourse.
3. The overlapping between the curves.

So the fuzzification is an important process to fuzzify scalar quantities to fuzzy quantities recognizable by the fuzzy system that will be developed. On the other hand, the plant model to which the output of the fuzzy system is going to be applied to can only recognize a scalar/crisp value; therefore, the output of the fuzzy system must be converted back to a crisp value to be recognized by the controlled system. The mechanism of obtaining a crisp set or a scalar value from the fuzzy set is called defuzzification.

Sometimes, crisp sets from a fuzzy set are required. And the way to obtain a crisp set from a fuzzy set is to use λ -cut set definition as follows:

$$\mu_{A_\lambda} = \begin{cases} 1; & \text{if } \mu_A(x) \geq \lambda \\ 0; & \text{otherwise} \end{cases} \quad 4.11$$

where A_λ is λ -cut set. Any element belongs to A_λ also belongs to the fuzzy set A with a grade membership greater than or equal to λ .

In most of the cases, a precise scalar quantity is required rather than a fuzzy set, and there are numerous ways from which a single scalar quantity can be obtained. The outputs of a fuzzy system depending on the inference mechanism used (explained later) can be the logical union of two or more membership functions defined on the universe of discourse of the output variable z for example. There are various defuzzifying methods that can be

applied to the resulting output shape to obtain the crisp value, and some of these methods are max membership principle, centroid method/center of gravity, weighted average method, and mean max membership.

The literature such as [1, 4] can be consulted to obtain more details on how to use these defuzzification methods to calculate the scalar quantity. It should be noted that out of the proposed defuzzification methods, the center of gravity is the most popular and appealing method, Fig. 4.4, and it is defined by the algebraic expression as:

$$z^* = \frac{\int \mu_c(z) \cdot z dz}{\int \mu_c(z) dz} \quad 4.11$$

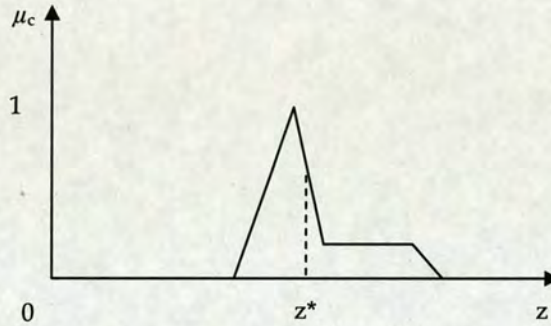


Figure 4.4 Centroid defuzzification method [1]

Having explained briefly the main concepts and operations of fuzzy sets and the concepts behind membership functions, the rule-based system or equivalently fuzzy system that express the subjective ideas of human reasoning in a natural language format will be explained.

4.3 Fuzzy Logic and System

The main goal of fuzzy logic is to represent uncertainties or ambiguities presented by complex problems of various disciplines. And the representations of these uncertainties and vague boundaries differ even for the same problem as they are interpreted differently by each individual. The truth of the understanding and expression of subjective ideas (i.e. ideas that bare various interpretations such as a pretty girl) in a fuzzy logic can no

longer be true or false only as in a binary or classical logic but rather has a degree of truth between true or false. This degree of truth is expressed on the unit interval $[0,1]$. Hence, it can be observed that fuzzy logic can give engineers flexibility to extend the classical logic (i.e. either true or false) to another level of reasoning in order to reach solutions that are unfeasible using classical logic. However, the reasoning to judge the truths of the individual's understanding of the uncertainties in problems using fuzzy logic is approximate.

So the ultimate aim of the successful technology of fuzzy logic is to form the theoretical foundation to reason approximately imprecise fuzzy ideas or propositions expressed in linguistic statements of the form IF-THEN. The way to do this is to assign a value between $[0,1]$ to the fuzzy proposition, P . The truth value of the fuzzy proposition is mapping from the unit interval $[0,1]$ to the universe U of truth values, T , as expressed by the expression:

$$T : u \in U \rightarrow (0,1) \quad 4.12$$

And the degree of the truth for the fuzzy proposition, P , assigned to fuzzy set A is equal to the membership grade of x in the fuzzy set A and can be expressed as:

$$T(P) = \mu_A(x) \quad 4.13$$

where μ_A is between 0 and 1. As with fuzzy sets, there are also operations defined for a fuzzy logic, and they are logical connectives of negation, disjunction, conjunction, and implication and expressed as follows for two different propositions: proposition P defined on fuzzy set A and proposition Q defined on fuzzy set B .

$$\text{Negation} \quad T(\bar{P}) = 1 - T(P) \quad 4.14$$

$$\text{Disjunction} \quad P \vee Q : x \text{ is } A \text{ or } B \quad T(P \vee Q) = \max(T(P), T(Q)) \quad 4.15$$

$$\text{Conjunction} \quad P \wedge Q : x \text{ is } A \text{ and } B \quad T(P \wedge Q) = \min(T(P), T(Q)) \quad 4.16$$

Implication [Zadeh, 1973]

$P \rightarrow Q$: if x is A , then y is B

$$T(P \rightarrow Q) = T(\bar{P} \vee Q) = \max(T(\bar{P}), T(Q)) \quad 4.17$$

Of these logical connectives, the implication connective proposed by Zadeh is of great importance as it evaluates the degrees of the truths for the fuzzy propositions expressed in a linguistic format. It is modelled in a rule-based form, IF-THEN, which is equivalent to the following fuzzy relation, $R = (A \times B) \cup (\bar{A} \times Y)$. The membership function of R is defined as follows:

$$\mu_R(x, y) = \max[(\mu_A \wedge \mu_B), (1 - \mu_A(x))] \quad 4.18$$

When the logical implication has the compound form

IF x is A , THEN y is B , ELSE y is C

The equivalent fuzzy relation R is defined as $R = (A \times B) \cup (\bar{A} \times C)$, and the membership function is expressed as follows:

$$\mu_R(x, y) = \max[(\mu_A \wedge \mu_B), ((1 - \mu_A(x)) \wedge \mu_C(y))] \quad 4.19$$

In addition, if the fuzzy information is expressed in a rule-based format, IF-THEN or antecedent-consequent, it is possible and feasible to derive the consequent of one of the fuzzy rules from the other rules using composition operations two of which are max-min and max-product compositions explained previously. For example, if we have [1]

Rule 1: IF x is A , THEN y is B .

Rule 2: IF x is A' , THEN y is B'

knowing the relation R of rule 1 and A' of rule 2, then B' can be inferred as $B' = A' \circ R$. One important point is that there is no unique inverse with the composition operation (i.e. $B \neq A \circ R$).

There exist other techniques to implement the fuzzy implication IF A , THEN B or $A \rightarrow B$ to obtain the fuzzy relation R . The following are some of the different techniques that are used to obtain the membership function values of the fuzzy relation R :

$$\mu_R(x, y) = \max[\mu_B(y), 1 - \mu_A(x)] \quad 4.20$$

$$\mu_R(x, y) = \min[\mu_B(y), \mu_A(x)] \quad 4.21$$

$$\mu_R(x, y) = \mu_B(y) \cdot \mu_A(x) \quad 4.22$$

Equation 4.21 is known as Mamdani's implication and is widely used for inference technique when designing a fuzzy system.

The problems with the classical methods of reasoning and solving problems is the language used to reach a solution has to be in a format recognizable by computers and unnatural to individuals. In addition, the information conveyed has to be precise and bears no uncertainties or vague boundaries. Alternatively, the utility of fuzzy logic provides individuals means to convey the fuzzy information in a language that is natural to them and easy to understand and express.

The natural language that is used to express human knowledge for the purpose of designing fuzzy systems is expressed in the form of IF-THEN and known as rule-based form:

IF premise (antecedent), THEN conclusion (consequent)

Naturally, when we use IF-THEN in our daily conversation, we deduce another fact or conclusion if we have prior knowledge about a fact. This form of knowledge representation is also used to infer a fact or conclusion from the premise in modelling some complex systems using fuzzy logic. The antecedent and consequent parts of the linguistic rules are expressed by linguistic variables which in turn are represented by fuzzy sets and logical connectives of these sets explained previously. And by using the knowledge of fuzzy sets and fuzzy logic, a compound fuzzy rule can be divided into a number of simple fuzzy rules as:

Rule 1: IF condition C^1 , THEN restriction R^1

Rule 2: IF condition C^2 , THEN restriction R^2

.....

Rule r: IF condition C^r , THEN restriction R^r

There are different techniques to decompose a compound rule into simple canonical form as above, and the most common techniques that involve multiple premises are either connected by logical conjunction and disjunction. For multiple conjunctive antecedents, the fuzzy rule is of the form:

$$\text{IF } x \text{ is } A^1 \text{ and } A^2 \dots \text{ and } A^L, \text{ then } y \text{ is } B^S \quad 4.23$$

the multiple antecedents can be reduced to a new fuzzy subset as

$$A^S = A^1 \cap A^2 \cap \dots \cap A^L$$

and the membership functions of A^S is expressed as

$$\mu_{A^S}(x) = \min[\mu_{A^1}(x), \mu_{A^2}(x), \dots, \mu_{A^L}(x)]$$

So the compound rule can be expressed

$$\text{IF } A^S, \text{ THEN } B^S$$

For multiple disjunctive antecedents, the compound fuzzy rule has the form as

$$\text{IF } x \text{ is } A^1 \text{ or } A^2 \dots \text{ or } A^L, \text{ then } y \text{ is } B^S \quad 4.24$$

and can be reduced to the form as

$$\text{IF } A^S, \text{ THEN } B^S$$

where the fuzzy set A^S is defined as

$$A^S = A^1 \cup A^2 \cup \dots \cup A^L$$

$$\mu_{A^S}(x) = \max[\mu_{A^1}(x), \mu_{A^2}(x), \dots, \mu_{A^L}(x)]$$

When designing fuzzy (rule-based) system, a number of rules are involved and not only one rule. The overall output is merely the aggregation of the consequent or conclusion of each individual rule contribution. The most common cases of aggregation are conjunctive systems of rules and disjunctive system of rules.

For the case of conjunctive system of rules, the fuzzy rules must be jointly satisfied and are connected by the logical connective “and”. This means the overall output (conclusion), y , is evaluated by the fuzzy intersection of each individual rule as:

$$y = y^1 \cap y^2 \cap \dots \cap y^r \quad 4.25$$

expressed by means of membership function as

$$\mu_y(y) = \min[\mu_{y^1}(y), \mu_{y^2}(y), \dots, \mu_{y^r}(y)] \text{ for } y \in Y$$

In the case of disjunctive system of rules, one of the fuzzy rules of the fuzzy rule-based system must be satisfied. These fuzzy rules are connected by the logical connective “or”. The aggregated consequent, y , is the fuzzy union of each individual rule contribution expressed as:

$$y = y^1 \cup y^2 \cup \dots \cup y^r \quad 4.26$$

and the membership function of y is expressed as:

$$\mu_y(y) = \max[\mu_{y^1}(y), \mu_{y^2}(y), \dots, \mu_{y^r}(y)]$$

The IF-THEN inference that has been explained so far shows how to implement it mathematically; however, when there are even a few canonical fuzzy rules involved in the fuzzy system, the process becomes tedious if attempts are made to solve or check the solutions manually. There exist proposed graphical methods that can be used to infer the solutions of a fuzzy system with a few linguistic rules. Some of the well-known graphical methods of deductive inference are Mamdani systems, Sugeno models and finally Tsukamoto models.

Of these proposed graphical methods, the Mamdani systems are widely used in design the process of a fuzzy system especially in MATLAB. It should be pointed out these methods can be applied to both fuzzified scalars values as well as membership functions acting as inputs to any fuzzy system. For Mamadni systems, there are different types of implication methods: (1) Mamdani (max-min) inference method and (2) Mamdani (max-product)

implication method bearing in mind the antecedent (inputs) and consequents (outputs) of a collection of linguistic rules can be of any number and connected by logical connectives “and” and “or” and are expressed in the Mamdani form as:

$$\text{IF } A \text{ is } A_1^k \text{ and } B \text{ is } B_2^k \text{ THEN } y^k \text{ is } C^k \text{ for } k = 1, 2, \dots, r \quad 4.27$$

where A_1^k and B_2^k are the fuzzy sets/membership functions that represent the k th input pairs, and C^k is the fuzzy set that represent the k th output.

In general, the aggregated output of Mamdani (max-min) inference method based on Eq. (4.21) and for a set of disjunctive rules is expressed as:

$$\mu_{C^k}(y) = \max_k [\min[\mu_{A_1^k}(\text{input}(i)), \mu_{A_2^k}(\text{input}(j))]] \quad k = 1, 2, \dots, r \quad 4.28$$

The following figure taken from [1] illustrates the aggregated output of two rules using Mamdani (max-min) inference method:

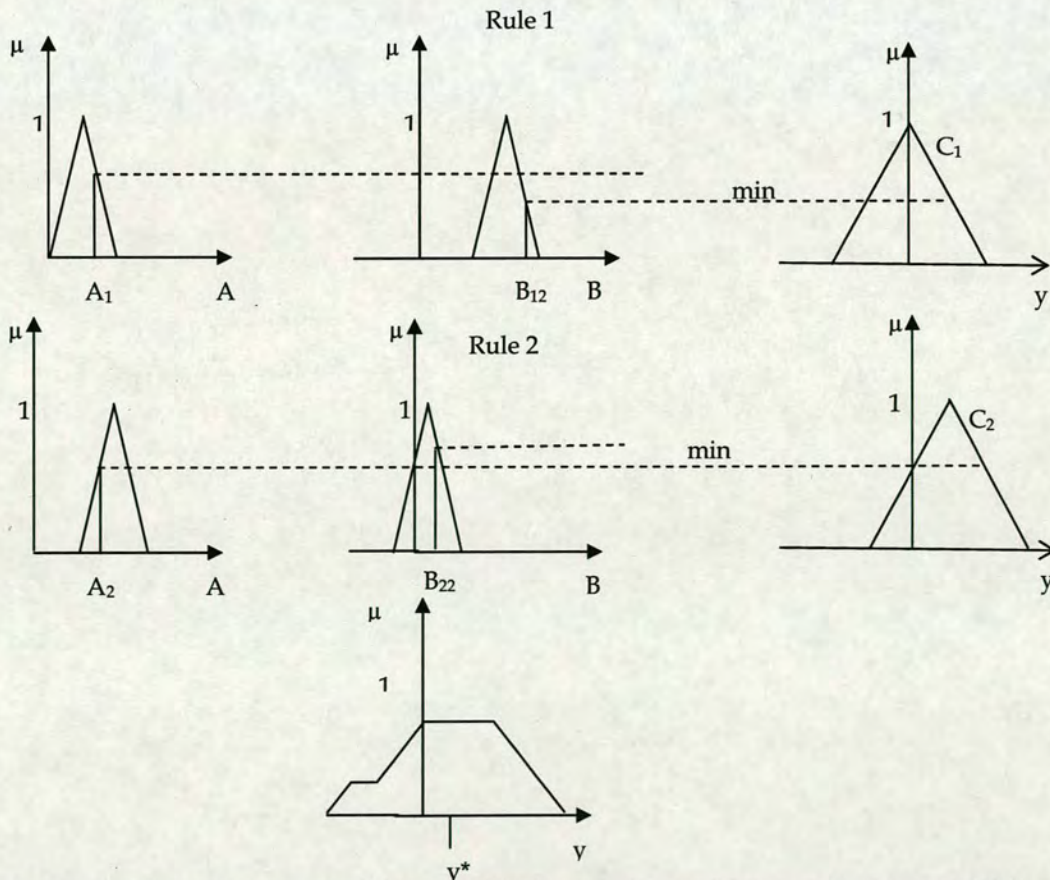


Figure 4.5 Graphical Mamdani (max-min) inference for two inputs and one output [1]

From the figure, it is shown that the minimum of the two inputs of a rule propagates to the output and in this case truncates it since the two inputs are connected by logical connective “and”. And the overall output, y^* , is the aggregation of the two individual outputs and any defuzzification methods explained previously can be used to get a crisp value. For the second Mamdani implication (max-product), the membership function of the aggregated output based on a set of disjunctive rules and Eq. 4.22 can be expressed as:

$$\mu_{C^i}(y) = \max_k [\mu_{A_1^i}(\text{input}(i)) \cdot \mu_{A_2^i}(\text{input}(j))] \quad k = 1, 2, \dots, r \quad 4.29$$

The corresponding consequent of each individual rule is a scaled triangle instead of truncated triangles as before. The following figure illustrates the Mamdani (max-product) implication graphically:

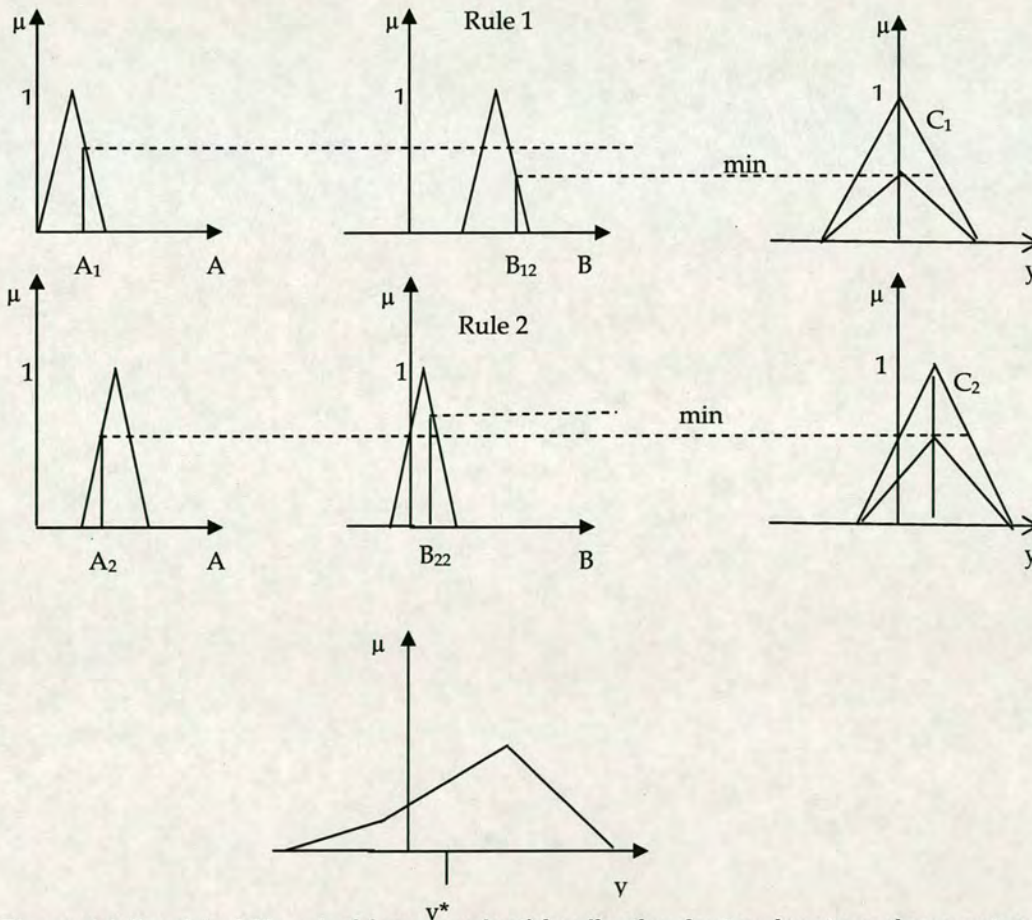


Figure 4.6 Graphical Mamdani (max-product) implication for two inputs and one output

[1]

For any fuzzy system description, the maximum number of IF-THEN canonical rules required depends on the number of partitions of the input(s) to the fuzzy system and is equal to

$$l = k_1 k_2 \dots k_n$$

where l is the maximum number of rules, and k_1 is the number of partitions of input A. But it is not imperative that a fuzzy system require the use of the maximum number of rules; it could be described and implemented with much fewer rules, r , than the allowable maximum rules, $r \ll l$. The following figure illustrates a decision table for a fuzzy system with two inputs, A and B partitioned to seven and five partitions respectively, and one output, C, partitioned into five partitions.

Input A								
Input B		A ₁	A ₂	A ₃	A ₄	A ₅	A ₆	A ₇
	B ₁	C ₁		C ₄	C ₄			C ₃
	B ₂		C ₁				C ₂	
	B ₃			C ₁			C ₂	C ₂
	B ₄	C ₃				C ₂	C ₁	C ₂
	B ₅	C ₃		C ₄	C ₄		C ₁	

Figure 4.7 Decision table for rule-based system

From Fig. 4.7, the number of fuzzy rules required for such system is only seventeen rules although the maximum allowable rules are $l = 7 \times 5 = 35$. The number of partitions of any input or output depends on the designers of the fuzzy system, there are no specific limitations on how many partitions an input or an output can have. Figure 4.8 illustrates five partitions of an input on the range of $[-1,1]$, and each partition is labelled so that it can be distinguished and used in the construction of the fuzzy rules.

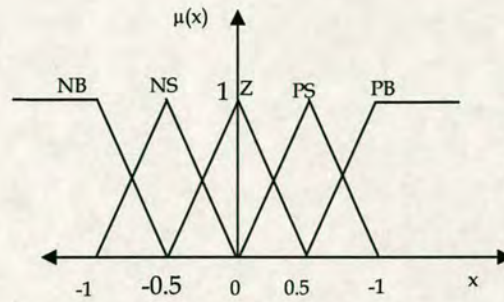


Figure 4.8 Partitions of input $x = [-1, 1]$

NB, NS, Z, PS, and PB correspond to negative big, negative small, zero, positive small, and positive big, respectively.

With the foundations and main concepts of fuzzy logic briefly explained, the utility of fuzzy logic theory to some power systems applications can be illustrated.

4.4 Application of Fuzzy Logic to Power Systems

Power systems are known to be large, complex, and of a non-linear nature; they are often prone to unexpected events which could have detrimental affects on the power systems as a whole. The rapid developments of expert systems and other artificial intelligence techniques have allowed engineers to improve the performance of the various components of the power systems, thus, improving the overall behaviour of the power systems. However, such techniques still cannot provide flexibility in representing the uncertainties and fuzzy nature of the problems that power systems encounter daily, especially when engineers prefer to express their knowledge and sometimes their abstraction about the problems in a natural language (i.e. if x_1 is small and x_2 is medium, y is likely to happen) [5]

Not only uncertainties can be a challenge for these techniques to accommodate but also the conflicting objectives within the power systems. Security, economy, generation costs, and last but not least the stability are some of the conflicting objectives that must be taken into account when trying

to solve power systems related problems. Alternatively, fuzzy logic has become the most attractive technology in recent years to solve power system problems that contain uncertainties and conflicting objectives because of its ease to use and implement and most importantly its nature of describing the control rules in a humanistic, linguistic format, IF-THEN.

Some of the areas in power systems that fuzzy logic has benefited are planning related areas, operation areas, diagnosis areas, and finally control areas. Of interest among these areas is the control area, specifically the design and implementation of power system stabilizers. For fuzzy logic control (FLC), the main objective is to realize the human control strategy to tackle control problems such as the stability of power systems [2, 4, 6, 7]. As mentioned previously, the use of FLCs has risen in recent years due to its lower computation burden, less time required to realize a control strategy, and lower development cost with better performance. In the first part of this section, the design procedure of fuzzy logic controllers will be covered. The second part is to describe briefly some of the fuzzy logic based power system stabilizers (FPSS) shown in the literature.

4.4.1 Design of an FLC

The main idea behind FLC is the fuzzifications of the controller inputs, rule definitions, rule inference, and defuzzifications, Fig. 4.9.

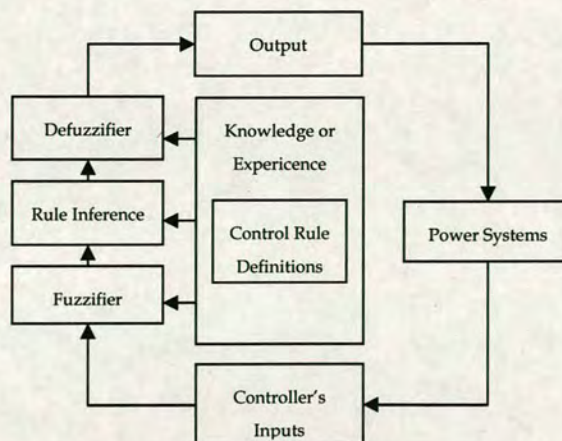


Figure 4.9 Design procedure of FLC

4.4.1.1 Fuzzification

The fuzzifications involve the transformation of crisp control variables to corresponding fuzzy linguistic variables. The types of input variables depend on the nature of the controlled system; it is customary in the literature to use the output error (difference between the output and set point) and derivative of the output error as controller inputs for the fuzzy logic based system. Since the aim here is to realize fuzzy logic based power system stabilizer (FPSS) to damp electromechanical oscillations, it is reasonable and generally the case to have the generator speed deviation $\Delta\omega$ and its derivative $\Delta\dot{\omega}$ as input signals to FPSS as the oscillations can be highly observable in the speed deviation. It should be pointed out that there are alternative signals that can be also used as inputs to FPSS along with speed deviation; some proposed signals in the literature are active power deviation and excitation voltage deviation [6, 7]. Logically, the signals that are easily measurable and contain valuable information about the disturbance are good input signal candidates.

The fuzzified input and output signals of FLC or FPSS are interpreted into a number of linguistic variables: Fig. 4.8 gives an example of an input signal that has five different linguistic variables namely NB, NS, Z, PS, and PB which stand for negative big, negative small, zero, positive small and positive big respectively. The required number of linguistic variables differs from one application to another; hence, there is no specific restriction on the number of linguistic variables. However, normally an odd number is used.

Each linguistic variable has a label and a membership function $\mu(x)$ to distinguish it from the others; the universe of discourse for each input and output is defined according to the controller designers; however, at the same time it should not exceed the operational limits of the power system component for which fuzzy system is designed. For example, the universe of discourse of the fuzzified output variable of FPSS should not exceed -0.1 - 0.1 (as recommended for conventional PSS). As for the membership shapes, it is

not necessary that the membership functions are of uniform shapes and overlap by %50 as shown in Fig. 4.3 which is used for a simplicity reason.

4.4.1.2 Rule Definitions and Inference Mechanism

Designing FLC involves the definitions of the control rules in the form IF-THEN. In a way, the fuzzy system maps the input fuzzy sets to the output fuzzy sets, and this is done through the control rules which create relations between input/output fuzzy sets as illustrated before.

In many cases, the control rules are derived based on the past experience, the knowledge during offline simulations, intuitions, an expert operator, understanding of dynamic system behaviour under control, and/or a design engineer who is involved with the power systems. For example, the control rules for FPSS can be formulated based on the action of a conventional PSS operating at a particular operating point. As a result, there is no generic methodology that can be defined for constructing control rules.

An advantage of fuzzy logic over other knowledge-based controllers is its requirement of fewer control rules due to the interpolative nature of the fuzzy control rules. The overlapping fuzzy antecedents to the control rules cause smooth transitions between the control actions of different rules [5]. The maximum number of the control rules depend on the number of linguistic variables for each input as stated before. Table 4.1 (5 x 5) decision table illustrates an example of two inputs fuzzy system associated with five linguistic variables each:

$\Delta\omega \backslash \Delta\omega$	NB	NM	Z	PM	PB
NB	NB	NB	NB	NM	Z
NM	NB	NM	NM	Z	PM
Z	NM	NM	Z	PM	PM
PM	NM	Z	PM	PM	PB
PB	Z	PM	PM	PB	PB

Table 4.1 Decision table of 25 control rules

An example of the i th rule is:

If $\Delta\omega$ is NB and $\Delta\omega$ is PM then U is NM

where U is the controller's output. This i th rule means that if the speed deviation is negative big and the acceleration is positive small, then the output controller should be negative small.

The control rules are evaluated simultaneously to infer the fuzzy system output. The inference mechanism consists of two processes called fuzzy implication and rule aggregation. Mamdani's implication (max-min) is usually used to infer the output of the i th rule. For example, if $\Delta\omega$ is NB with a membership degree of 0.4 and $\Delta\omega$ is PM with a membership degree of 0.7, the degree of firing the rule is 0.4. Then through the Mamdani's implication, the degree of firing the rule interacts with its consequent to provide the output of the rule as in Fig. 4.5.

4.4.1.3 Defuzzification

The last process of FLC is the defuzzification. The defuzzification mechanism is to convert a fuzzy value/set to a crisp value/set so that the controlled object can interpret the controller's output accordingly. The wide practice method of defuzzification is the centre of gravity. The FLC design procedure

explained is applicable to any application and not restricted to the design of power system stabilizer.

4.4.2 Fuzzy Logic Power System Stabilizers

Power system stabilizers are used to improve the dynamic performance of power systems that suffer electromechanical oscillations. The most widely used scheme to improve stability and reliability of power systems is the lead-lag PSS known also as a conventional PSS explained in chapter 2. Self-tuning techniques have been proposed to fix the shortcomings of the fixed parameters of conventional PSS; nonetheless, adaptive PSS suffers also a drawback. It requires a model identification in a real-time which means that a long process time is needed especially for a microcomputer with limited computational capability.

Literature shows an alternative PSS design scheme based on the flexibility and virtues of fuzzy logic such as it requires no model identification at all as the adaptive techniques require. There are several attempts reported in the literature and only a few will be described.

Reference [8] describes the design procedure of FPSS for multi-machine power systems. The proposed input signals for FPSS uses two real-time measurements $\Delta\omega$ (generator speed deviation) and its derivative $\Delta\dot{\omega}$ (acceleration). The design steps follow exactly the procedure described previously of FLC with the exception that the measured stabilizer inputs speed deviation and acceleration are normalized based on previous experience as:

$$\Delta\omega_u = \frac{\Delta\omega}{0.01} \quad 4.30$$

$$\Delta\dot{\omega} = \frac{\Delta\dot{\omega}}{0.001} \quad 4.31$$

The main features of proposed FPSS is that (1) very efficient and easily implemented on a microcomputer as it does not require model identification as always the case with every proposed FPSS, (2) the proposed FPSS is of decentralized output feedback form as local stabilizer inputs are measured from each synchronous generator in multi-machine model, and finally the results in [8] show that FPSS provide better dynamic performance over a wide range of operating conditions.

The authors tested the proposed FPSS on two generators of a multi-machine whose response was observed without stabilizers, with conventional stabilizers equipped to some machines, and with FPSS equipped to some generators. Test results revealed interesting conclusions that when one of the generators was equipped with the decentralized FPSS, the overall response of the power system still performed better than with conventional PSS equipped to two machines. Because it seemed the second generator not equipped with FPSS benefited from FPSS on the other generator via the transmission links between them. Another interesting observation according to the authors was when both generators were equipped with FPSS, the FPSSs co-operated with each other very well to provide better damping performance under disturbance conditions.

Another proposed rule-based fuzzy PSS in the literature is [2] where the proposed FPSS is tuned by a neural network. The tuning by a neural network makes FPSS more adaptable and flexible than it already is to changes in operating conditions.

FPSS is designed according to FLC steps as usual. The main contribution of this paper [2] is the tuning procedure using neural network. To tune FPSS, the speed deviation and accelerating power which are inputs to FPSS are scaled according to the following relations respectively.

$$\Delta\omega^* = K_p \cdot \Delta\omega \quad 4.34$$

$$\Delta P^* = K_d \cdot \Delta P \quad 4.35$$

where K_p and K_d are the speed and acceleration scaling factors, respectively. The output of FPSS is also scaled according to a similar relation in which the scaling factor for output u is fixed to a suitable number, i.e. 0.5 for the system under study. The optimum K_p and K_d are computed according to a neural network as shown in Fig. 4.8.

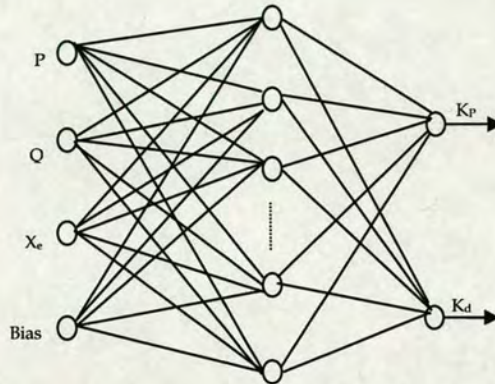


Figure 4.10 Neural network configuration for calculating optimum scaling factors

The generated active power P and reactive power Q are used as inputs for neural network to represent the operating condition of the synchronous machine. X_e total reactance of the transmission line represents the external information, and a bias signal is injected to the neural network to reduce the required learning time. From various combination of the input data, optimal parameters of the FPSS are searched. From Non-linear simulation results, optimum response of the system can be obtained for a wide range of operating conditions compared to a fixed-parameters FPSS and a linear conventional PSS. Thus, Further improvements to FPSS are achieved.

Abundance of information is listed in the literature in relation to fuzzy logic (rule-based) power system stabilizers [2, 6-13]. FLC design procedure is followed in the literature as one might notice.

4.5 Conclusion

Fuzzy logic provides individuals flexibility in expressing their subjective or fuzzy ideas in fuzzy sets on the range of $[0,1]$ or between true/false; whereas,

in the past fuzzy ideas or understanding can be either true or false. The extension of fuzzy set theory and fuzzy logic from classical set theory and binary logic makes fuzzy logic easy to use and implement for different application. In addition, the fuzzy logic control or known as rule-based control allows control engineers to express their reflection of understanding on how to control an object in a humanistic form, *IF-THEN*. It allows design engineers to realize a control strategy in less time, lower cost with much better performance compared to classical methodologies. Therefore, fuzzy logic has become the most widely used technology in recent years to develop sophisticated control systems, yet, easy to implement and design.

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Chapter 5

Test Systems Modelling

5.1 Introduction

IN conventional electrical power systems, the primary sources of electrical energy are the synchronous generators that must be kept in synchronism when interconnected to ensure small-signal stability (small disturbance) at all times [1]. From the viewpoint of power system, other components such as speed governors and excitation systems must also contribute to the enhancement of the system stability. Moreover as the modern power system increases in size, so too does the complexity of the non-linear dynamic behaviour of such a system. In addition, understanding the underlying physical phenomena behind the various non-linear parts of the power system becomes more challenging for analysis and control design. Therefore, proper understanding and modelling of such components are vital for stability studies.

In this chapter, an overview of the three different test systems considered for this research is given along with a brief description of other components used in power system stability study.

5.2 Case Study Models

Three different test models have been used. The first model is the well-known benchmark Kundur's four-machine two-area system [1]. This model is the building block that is used to derive the general control rules for the proposed fuzzy-based supervisory power system stabilizer (SPSS). The second test case is a six-machine three-area system which is merely an expansion of the two-

area system mentioned, and it is used to demonstrate the effectiveness of the fuzzy-based SPSS on a larger power system model compared to the four-machine two-area system. The third is a major dynamic model used as the primary test case for this research, and it consists of a 16-machine 5-area system which is a reduced order equivalent of the inter-connected New-England test system (NETS) and New York power system (NYPS). The two small dynamic models are used for testing and development of SPSS; whereas, the 16-machine 5-area system is used to validate the proposed SPSS structures. Detailed information about all test systems including controller parameter values can be found in Appendix A.

5.2.1 Four Machine Two Area Test System

The four-machine two-area test system, which is shown in Figure 5.1, has been specifically designed and commonly used in other studies and literature to thoroughly study the fundamental behaviour of large inter-connected power systems in particular and to gain knowledge of the fundamental nature of inter-area oscillations [1-3]. Although it is hypothetical and a simple model, the system structure and parameters are realistic.

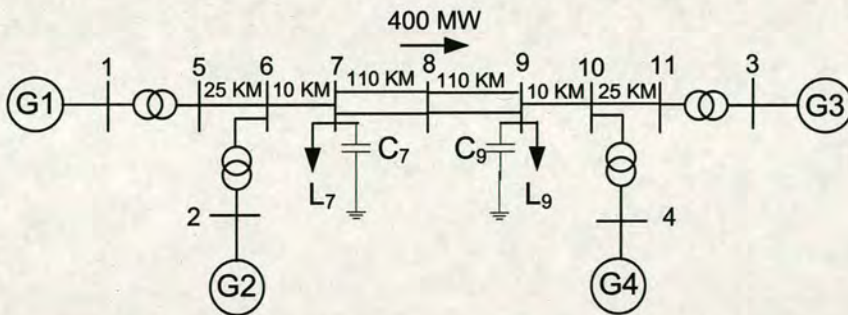


Figure 5.1 Line-diagram of 4-machine 2-area system

This system is used in this dissertation to initially derive the general control rules for fuzzy-based SPSS as stated previously and test fuzzy-based SPSS prior to its validation on a larger system. The system consists of two identical areas connected by a weak tie-line, and each area consists also of two identical

generating units with a rating of 900 MVA and 20 kV each. The system is exporting 400 MW to area 2.

Generators G1 to G4 are each equipped with IEEE high-initial response excitation system (IEEE Type AC4A Excitation System) and governor (Steam Type Governor) controllers. The parameters for the standard exciter and governor controllers used for the simulations are taken from [1]. For stability study and controller design, designers adopt various simplified generator models as it is recommended in the literature. Hence, for each synchronous generator in all test models in this research is represented by 5th order dynamic model whose nonlinear differential and/or algebraic equations as well as notations can be also found in [1]. This will be briefly described later on.

The loads for this dynamic model and for all other test systems are modelled as constant admittances. An advantage of the assumption of constant admittance loads is that it is possible to eliminate the network nodes to obtain an equivalent system which only consists of nonlinear differential equations. In addition, it will be possible to simplify the process of computing the new voltages at the network nodes with sources of energy only [4]. This can be achieved by the following steps:

1. Pre-fault load flow calculation is performed. The equivalent steady-state impedance loads is calculated in the form of admittances as

$$y_{LK}^* = \frac{P_{LK} + jQ_{LK}}{V_k^2}, \text{ where } k = 1, 2, \dots$$

for each load. Once these elements are calculated, they are added to the corresponding elements in the \bar{Y}_{bus} , admittance matrix.

2. The internal machines voltages are calculated for each of the n machines.

3. \bar{Y}_{bus} is augmented by admittances corresponding to internal machine nodes/buses and load buses. The augmented matrix can be symbolically partitioned as

$$\hat{\bar{Y}}_{bus} = \begin{bmatrix} \bar{Y}_a & \bar{Y}_b \\ \bar{Y}_c & \bar{Y}_d \end{bmatrix} \begin{matrix} n \\ N \end{matrix}$$

where n are internal machine nodes and the remaining N are load buses (i.e. network nodes). The nodal equations which represent the relation between injected currents and node voltages is now given by

$$\begin{bmatrix} \bar{I}_G \\ \bar{I}_L \end{bmatrix} = \begin{bmatrix} \bar{Y}_a & \bar{Y}_b \\ \bar{Y}_c & \bar{Y}_d \end{bmatrix} \begin{bmatrix} \bar{V}_G \\ \bar{V}_L \end{bmatrix}$$

where \bar{I}_G and \bar{V}_G represent vectors of source currents and voltages respectively. Whereas, \bar{I}_L and \bar{V}_L are vectors of currents injected by the loads and node voltages at load buses, respectively. Since there are no injected currents in the network nodes, $\bar{I}_L = 0$, this system is reduced to internal machine nodes as follows

$$\bar{V}_G = \frac{\bar{I}_G}{\bar{Y}_{int}}$$

where the matrix of admittance \bar{Y}_{int} is given by

$$\bar{Y}_{int} = (\bar{Y}_a - \bar{Y}_b \bar{Y}_d^{-1} \bar{Y}_c)$$

With the load nodes having zero current injection, the system matrix is reduced as above. Figure 5.2 depicts the synchronous machines with reduced network matrix of admittance

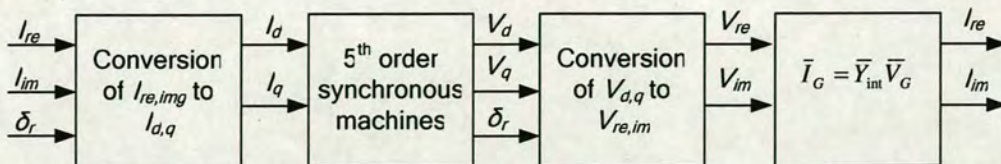


Figure 5.2 Modelling of generators with input currents and output voltages

Furthermore, each fast-acting exciter for this dynamic model is equipped with a power system stabilizer (PSS) to provide supplementary damping control for electro-mechanical oscillations. The feedback signal for the input of each local PSS is the measured active power of i th generator (i.e. G_1). The dynamic response of the PSS is modelled by:

$$V_{pssi} = K_{pssi} \frac{sT_{\omega} (1 + sT_{1i}) (1 + sT_{3i})}{(1 + sT_{\omega}) (1 + sT_{2i}) (1 + sT_{4i})} \quad 5.1$$

where the notation carries their standard definitions as in [5]. In order to obtain an oscillatory but stable system (low damped inter-area electromechanical modes), local PSS gain K_{pssi} is artificially reduced whenever there is PSS equipped in all test models to show how fuzzy-based SPSS help damp inter-oscillations. The general structure of the i th-machine together with local PSS in a multi-machine power system is shown in Figure 5.3 [6].

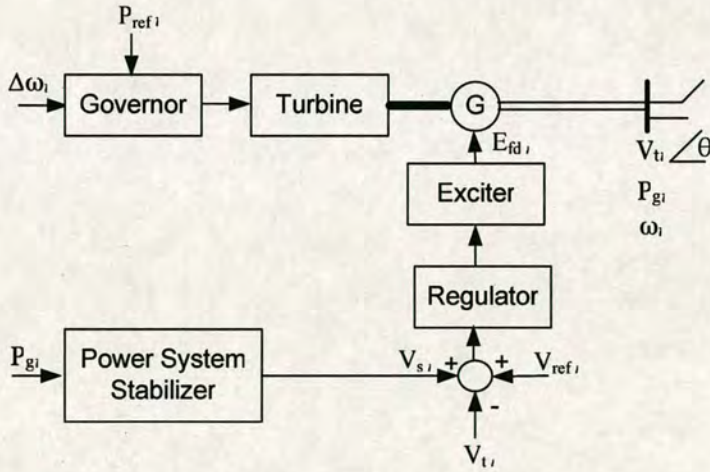


Figure 5.3 Schematic diagram of the i th-generator together with PSS in a multimachine model

Power systems are most naturally described by non-linear differential and/or algebraic equations (DAE) which are combination of the dynamic models of the individual components comprising power systems. The differential and algebraic equations governing the 5th order synchronous machine model used for all test cases are given as in [1] in the d-q reference frame in per unit by:

Rotor voltage equations

$$e_{fd} = p\psi_{fd} + R_{fd}i_{fd} \quad 5.2$$

$$0 = p\psi_{1d} + R_{1d}i_{1d} \quad 5.3$$

$$0 = p\psi_{1q} + R_{1q}i_{1q} \quad 5.4$$

Rotor flux linkage equations

$$\psi_{fd} = L_{ffd}i_{fd} + L_{f1d}i_{1d} - L_{ad}i_d \quad 5.5$$

$$\psi_{1d} = L_{f1d}i_{fd} + L_{11d}i_{1d} - L_{ad}i_d \quad 5.6$$

$$\psi_{1q} = L_{11q}i_{1q} + L_{aq}i_{2q} - L_{aq}i_q \quad 5.7$$

Stator flux linkage equations

$$\psi_d = -(L_{ad} + L_l)i_d + L_{ad}i_{fd} + L_{ad}i_{1d} \quad 5.8$$

$$\psi_q = -(L_{aq} + L_l)i_q + L_{aq}i_{1q} + L_{aq}i_{2q} \quad 5.9$$

Mechanical dynamic equation

$$\frac{d\Delta\omega_r}{dt} = \frac{1}{2H}(T_m - T_e - D\Delta\omega) \quad 5.10$$

$$\frac{d\delta}{dt} = \omega_s\Delta\omega \quad 5.11$$

for $k = 1$ and 2 , where,

e_{fd} : field voltage,

ψ_{fd} , ψ_{kd} , ψ_{kq} : rotor circuit flux linkages,

R_{fd} , R_{kd} , R_{kq} : rotor circuit resistances,

i_{fd} , i_{kd} , i_{kq} : field and amortisseur circuit currents,

L_{ffd} , L_{11d} , L_{11q} : self-inductances of rotor circuits,

L_{ad} : d-axis mutual inductance,

L_{aq} : q-axis mutual inductance,

L_l : stator leakage reactance,

$\Delta\omega_r$: rotor angular speed deviation,

T_m : mechanical torque,

T_e : electrical torque,

D : mechanical damping constant,

H : inertia constant of generator,

ω_ω : synchronous speed, and

δ : generator rotor angle.

The notation is standard also as in [1]. In per unit, the subtransient, transient, and synchronous reactances are equivalent to the corresponding inductances. Therefore, common industry practice is to express synchronous machine parameters in terms of reactances instead of inductances. All the dynamic data for the test models and equations to calculate machines' resistances and reactances used in the previous equations are given in Appendix A. The following figure summarizes the overall nonlinear modelling and simulation of large power system

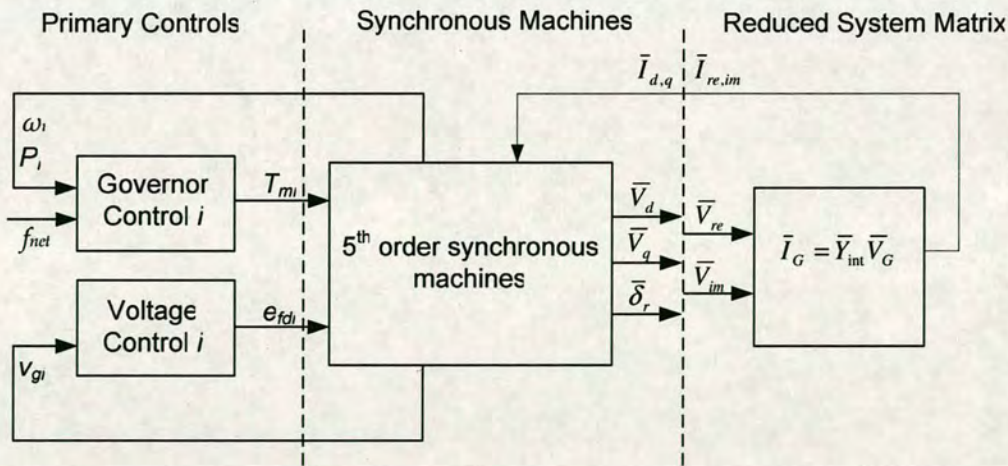


Figure 5.4 Simulation of large power system with constant impedance load type

5.2.2 Six Machine Three Area Test System

The second test system consists of three areas and six synchronous machines. This system is merely an expansion of the 2-area 4-machine model explained previously. However, the parameters of synchronous generators in all three areas as well as system structures are realistic. The generating units in area 1 and area 2 are all identical, and each generating unit is with a rating of 900 MVA and 20 kV. Similarly, area 3 also consists of two identical generating units whose rating is 555 MVA and 24 KV each. The synchronous machines parameters in area 3 are taken from [1]. Figure 5.5 shows a schematic diagram of the 3-area 6-machine test system illustrating major transmission and generating units as well as geographical areas.

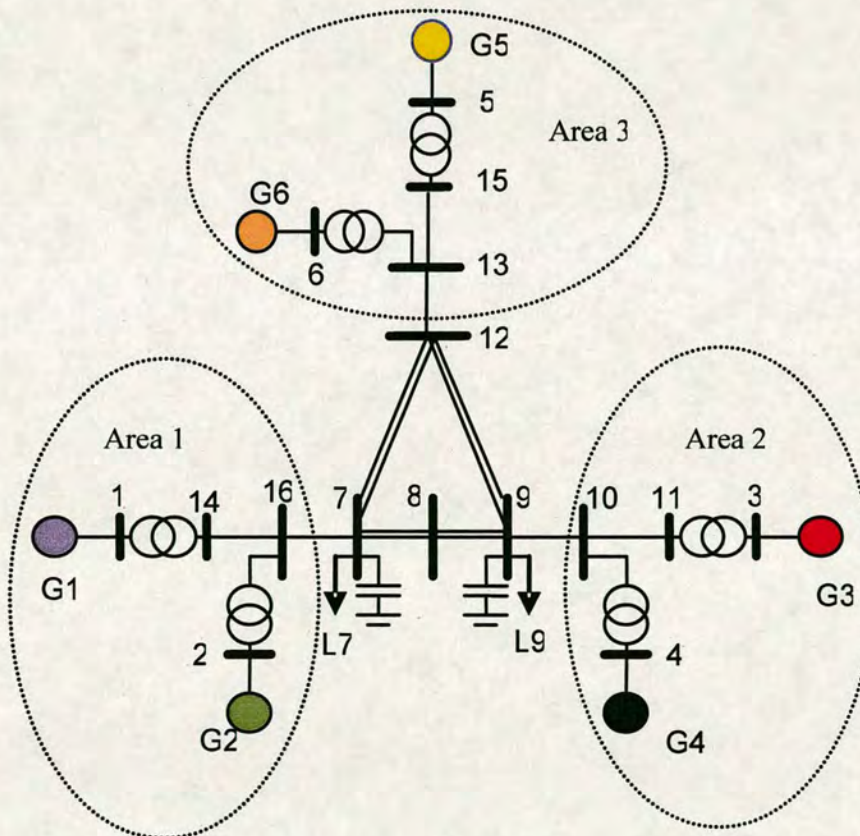


Figure 5.5 Schematic diagram of 3-area 6-machine test system

This model used in this analysis contains 16 buses and 6 synchronous generators each of which is modelled as 5th order dynamic model. Each synchronous machine is equipped with IEEE standard fast acting excitation

system (IEEE Type AC4A Excitation System) and governor (Steam Type Governor) controllers, and they are taken from [1]. Furthermore, the high-initial response excitation system for each generating unit is equipped with local power system stabilizer that uses measured local active power as an input variable. The system follows the same reduction of system matrix with the assumption of constant loads as for the 2-area 4-machine model.

5.2.3 Sixteen Machine Five Area Test System

The third test system considered is a 16-machine 5-area system. This dynamic model is reduced order equivalent of the inter-connected New England test system (NETS) and New York power system (NYPS) which is taken from [7]. The test system contains 68 buses out of which sixteen buses are generator buses as shown in Figure 5.6.

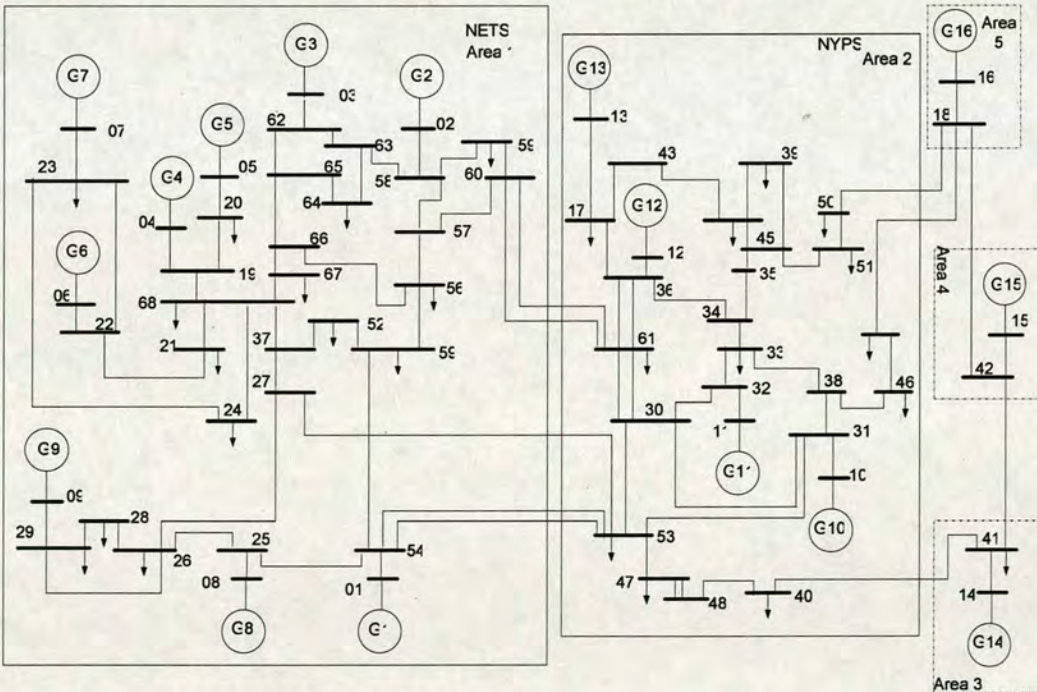


Figure 5.6 16-Machine 5-Area study system

There are five geographical regions out of which NETS and NYPS are represented by a group of synchronous generators; while, import of each of the other three remaining regions, denoted by Area 3, Area 4 and Area 5 are

approximated by equivalent generator models. The power exchange between NETS and NYPS is transferred through major transmission corridors by the connecting bus numbers 60-61, 53-54 and 27-53. All these transmission corridors have double-circuit tie-lines which carry total tie-line power exchange between NETS and NYPS of approximately 700 MW.

All the synchronous generators are represented by 5th order dynamic model as in the case for the other test systems. G1 to G8 are equipped with IEEE slow excitation systems, namely IEEE-DC1A; whereas, G9 is equipped with a fast acting static excitation system, IEEE-AC4A, and a speed-based power system stabilizer (PSS) to ensure adequate damping for its local oscillation [1, 7]. This is the only machine equipped with local PSS. Since the objective is to validate the supervisory power system stabilizer on a larger test system, our concern or focus is not to design or set parameters of local power system stabilizers for the other machines but the aim is to show robustness and applicability of SPSS. G14 to G16 are also equipped with high-initial IEEE static excitation systems, IEEE-AC4A. The rest of the generators are under manual excitation control. The reduction of the system matrix is achieved by matrix algebra as shown before on the assumption that all loads are treated as constant impedance (i.e. zero current injection).

5.3 Conclusion

In power systems, synchronous generating units are the main source of electrical energy supply via high-voltage transmission lines and low voltage distribution system. The stability of the power system depends on the controllers connected to the system such as excitation systems. Therefore, proper understanding and modelling of characteristics of such components is a matter of fundamental importance for stability studies. In this chapter, the aim then is to present to the readers with proper understanding of the mathematical modelling associated power system. A brief description is of

system modelling is provided along with illustrated figures. Finally, the three test systems used to validate the proposed supervisory power system stabilizer (SPSS) are explained in details.

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Chapter 6

Methodology of Supervisory Power System Stabilizer

6.1 Introduction

IN recent years, the concept of centralized damping controller to effectively improve small-signal stability for large interconnected power systems has become a predominant interest for power system utilities and industry as illustrated in a previous chapter. Since such proposed centralized damping controllers can increase the operational limits (i.e. power interchanges between regions) of the power systems that are forced especially after de-regulation of the sector to operate in stringent operational requirements to maintain reliable service and adequate system dynamic performance. Furthermore, the trend of increasing power demands transmitted through the weak-tie lines is not going to ease up in the foreseeable future which will unfortunately result in further stringent requirements to maintain reliability and stability of the power systems. One of the possible control schemes that can be used to enhance small-signal stability and stability margin is based on fuzzy logic.

Fuzzy logic has been widely utilized and in fact its popularity is on the rise in most of today's practical application designs [1]. This can be attributed to its lower computational burden and its humanistic nature to represent the control actions/rules that must be taken by the proposed controllers to achieve a given goal.

In this chapter, the methodology that is used to design the general fuzzy based control rules to improve damping of electro-mechanical oscillations is

illustrated. Next, a description of the proposed input signals used for the supervisory power system stabilizer is discussed. And finally, the various proposed design structures for the centralized damping controller are explained.

6.2 Proposed Signal Type

Proper choice of an input signal to a fuzzy-based controller depends on the criteria and action required by the controller to be taken. A general rule of thumb is that the signal with the most observability of the system's state deviations from a stable operating point or a set point is most likely a good candidate to be an input signal to the proposed controller. This is because with high visible deviations/errors from a set point in such signal(s), fuzzy logic decision system (i.e. control rules) can be derived to rectify the deviations/errors. Since any fuzzy logic based controller requires at minimum two inputs, other possible input variables include variations (derivatives) of the state error/deviation and accumulation (integral) of the states error/deviation [1, 2].

Since the aim of the proposed of supervisory power system stabilizers is to enhance small-signal stability, in particular by increasing inter-area electro-mechanical oscillation damping, a common sense choice is to choose an input signal in which the electro-mechanical oscillations of interest are clearly visible. The second criterion which is recommended to be adhered to when determining the proper signal type for the proposed SPSS is to choose variable(s) that have significant effects on improving damping of the generators' shaft electro-mechanical oscillations.

From the literature [2-4], inter-area electro-mechanical oscillation modes which are of interest in this thesis are highly observable both in the active power of tie-lines between areas involved and in speed deviations of synchronous generators. Therefore, it is not unexpected to choose either one

of them as possible input signal to SPSS. But since the global information to be used as inputs for the proposed fuzzy-based SPSS is based on speeds/speed deviations or active power of tie-lines between regions/areas, the boundaries of these regions/areas that contain coherent groups of generators must be well defined and known before hand; otherwise, the SPSS damping signals might have detrimental consequences as will be explained later. For example, for high-voltage lines the power exchanged between regions can be measured as long as the coherent group boundaries are clearly defined; that is to say the system configuration remains the same. However, if the system configuration changes as a result of load generation changes or generator disconnection for instance, the new regions/areas must be defined prior to determining the new power exchange between regions or even speeds of regions. It should be noted that the system configurations are sometimes assumed the same for some power systems and are known before hand especially if they are connected by weak tie lines as in the case of the widely used the 2-area 4-machine benchmark model illustrated in chapter 5.

As stated before, in the case where the coherent group boundaries are changing, the new system configuration must be determined and identified by using proper tools. Furthermore, when there are also weak connections within the subsystem/area, there might be group of generators swinging against each other. So theoretically for some proposed supervisory power system stabilizers whose inputs depend on information between regions/areas, there is a necessity to have some algorithm of coherent recognition which is an additional step beyond the scope of this thesis [5]. This process must be repeated every time a new system configuration takes place which unfortunately could be a limitation factor for some types of SPSS design structures explained later. Therefore, not knowing accurately the new coherent group boundaries, it would be most likely difficult to measure or define the power exchanged between areas accurately. The same argument can be drawn for speeds since theoretically measuring speeds of areas is as difficult as measuring the power interchanges between regions if new

boundaries of areas/regions are formed every time the system configuration changes. In our test models, the boundaries of the coherent groups of generators are assumed and in fact remain the same regardless of any changes to the old system configuration [6-8]. Nonetheless, for one of the proposed supervisory power system stabilizers (Type 1 SPSS) discussed in section 6.3 the inputs depend on either individual speeds/speed deviations or powers of generators rather than on speeds/speed deviations or tie-line power between regions/areas, then the boundaries of regions/areas have no influence on the inputs or physical meaning. And the problem of coherency is avoided.

A fuzzy logic controller requires two input signals. As it was shown in chapter 3, typical input signals to PSS are the local speed deviation/speeds and the generated power. In this research, differences in speed deviations/speeds between individual generators (Type 1 SPSS) or between areas (Type 2 or 3 SPSS) have been chosen as the input signals for the SPSS. The second input is merely the derivative of the first input. The importance of this signal is that it carries a physical significance: from the derivative of the speed/speed deviation (i.e. acceleration), we can infer whether or not the speed is in increasing or decreasing direction which in turn can provide more information about the swinging of the machine rotor. This is quite important when it comes to deriving the control rules later on. Furthermore, when we take such signals (i.e. speed difference), we could compare speeds between two individual generators or areas, and we could subtract them. The speed difference either between individual generators or areas has a physical meaning also. Power difference (between generators or areas) signal was also considered as an alternative second input to SPSS. There is some information in power difference but it would be system specific depending on the connection between generators and areas, the inertia of generators in a question, etc. Besides, when speed/speed deviation is used, there is no necessity to change membership function of the inputs when the operating point (power generated) is changing. We can assume that frequency reference

is constant and equal to 50Hz all the time (and then reference speed is also constant).

While using generator active power as input it would be necessary to shift (change) membership function after each change of power generated. It is not easy in practice because the output power varies constantly (as result of boiler and steam parameters variation, action of controllers, operators etc.). Also, the results from this literature show increasing and encouraging improvement of electro-mechanical oscillation damping when speed deviation is chosen as an input signal for the fuzzy-based local power system stabilizers. With the recent advances in the field of phasor measurement units (PMUs), the global signals can be easily obtained remotely to be used for control purposes.

6.3 Types of Fuzzy-Based SPSS Implementations

Using the same fuzzy control rules derived in subsequent section, three different types of centralized supervisory power system stabilizers are presented in this section. Each SPSS type is based on fuzzy logic. And it must be emphasised again that all the signals are fetched globally using the advanced technology of PMUs, and the three different SPSS controller types are centralized.

6.3.1 Type 1 Fuzzy-Based Supervisory Power System Stabilizer

In the first proposed design structure, the basic idea is to have one synchronous generator as a reference generator, G_o , so that each input signal injected to the SPSS will be the speed deviation difference $\Delta\omega_{ni}$ between the speed deviation of the reference generator, $\Delta\omega_o$, and the speed deviation of the i th generator, $\Delta\omega_i$, to which SPSS signal is going to be applied:

$$\Delta\omega_{ni} = \Delta\omega_o - \Delta\omega_i \quad 6.1$$

Since fuzzy controller requires at least two input signals for the fuzzy control rules to be evaluated, the other input signal will be the derivative of each $\Delta\omega_{ni}$ calculated in equation 6.2 for i th generator. For this design structure, the number of the stabilizing signals generated from the SPSS is equal to $n-1$, where n is the number of synchronous generators in the multi-machine model only to which SPSS is going to be applied. In other words, only synchronous generators which are not treated as a reference generator will be influenced by the SPSS's output as long as the corresponding $\Delta\omega_{ni}$ (i.e. speed deviation difference between reference and i th generators) is injected as an input to the SPSS. To illustrate the idea, Figure 6.1 demonstrates the structural technique behind Type 1 SPSS:

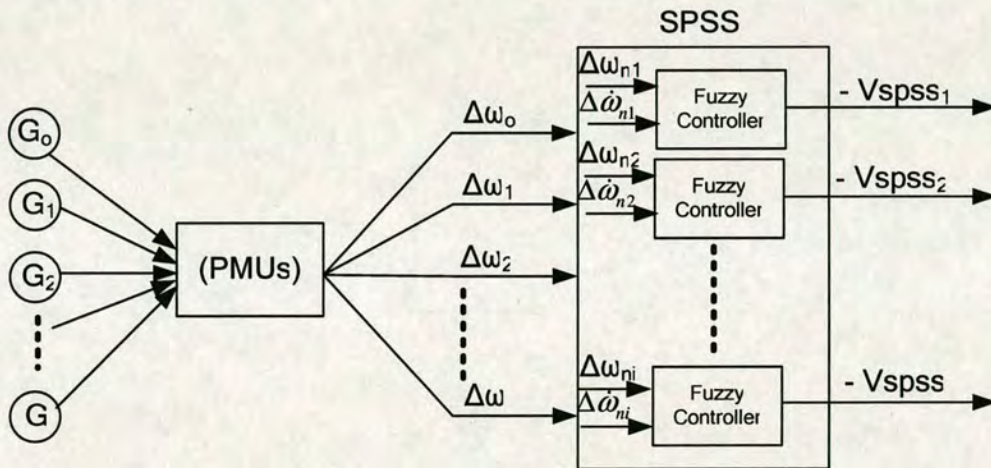


Figure 6.1 Type 1 SPSS structure

V_{spssi} represents the proper stabilizing signal that will be introduced to the excitation system of the corresponding i th generator, as in Figure 6.2, to increase the damping torque of the i th synchronous machine and consequently improve the overall system damping as it will be shown in chapter 7. Based on the proposed general decision table, Table 6.1 presented later on, the complete description of the fuzzy control rules for Type 1 SPSS is given in Appendix B.

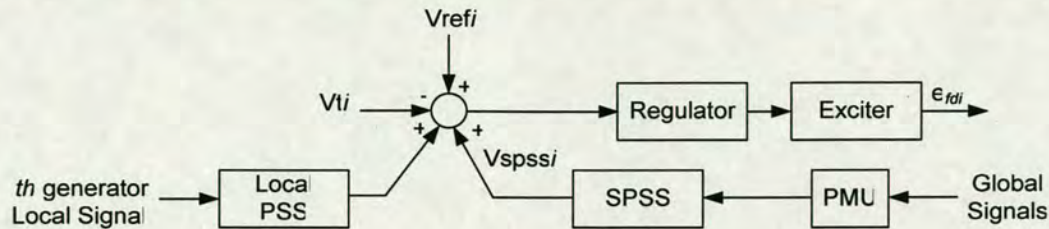


Figure 6.2 General structure of the i th-generator together with SPSS signal

For all the tests models in this thesis, synchronous generator one, G_o , is always taken as a reference generator on the basis that G_o is always assumed and considered to be connected to the slack node in the power flow calculation in MATLAB/SIMULINK. The advantage of this structural design of SPSS is that the boundaries of areas/regions (which contain a group of synchronous generators) disappear and have no significance or meaning and most importantly have no an adverse affect on the behaviour of SPSS. This is important because the speed deviation difference calculated, $\Delta\omega_{ni,r}$, is not influenced by any new system configuration that might form as a result of load change or power generation change. In other words, the speed deviation difference between a reference generator and the i th generator as mentioned before remains the same regardless if this i th generator becomes a member of another area or not in the new system configuration which might not occur at all if the configuration of the power system is not susceptible to changes in it (i.e. load increase).

6.3.2 Type 2 Fuzzy-Based Supervisory Power System Stabilizer

The concept behind the second proposed centralized controller is to introduce the n th stabilizing signal from the supervisory power system stabilizer to the synchronous generators of the i th area involved in increasing the damping the electro-mechanical oscillations. The implementation and structural design of Type 2 SPSS uses the same control rules derived in section 6.4; however, there are some aspects that differentiate Type 2 SPSS from Type 1 SPSS. The first aspect is the number of inputs to the fuzzy controller. Second, it is the method

in calculating the input signals and finally each i th stabilizing signal is mainly introduced to the corresponding i th area; whereas, in Type 1 each stabilizing signal is dedicated to a corresponding synchronous machine.

Figure 6.3 shows the overall general structure of Type 2 SPSS. As evident from the figure, the first step to implement Type 2 SPSS is to calculate the average speed deviations of the synchronous generators in the i th area of the multi-machine model. Moreover, for each i th area it should be emphasized that only the speed deviations of synchronous generators which are involved in the i th area to increase damping of electro-mechanical oscillations are averaged out. In other words, if there are in the i th area synchronous generators that are equipped with manual excitations as in the case of 16-machine 5-area multi-machine test model, their speed deviations are not taken into consideration when the average speed deviation of the n th area is determined. Once the average speed deviation of each area of interest is calculated, the speed difference between the average speed deviations

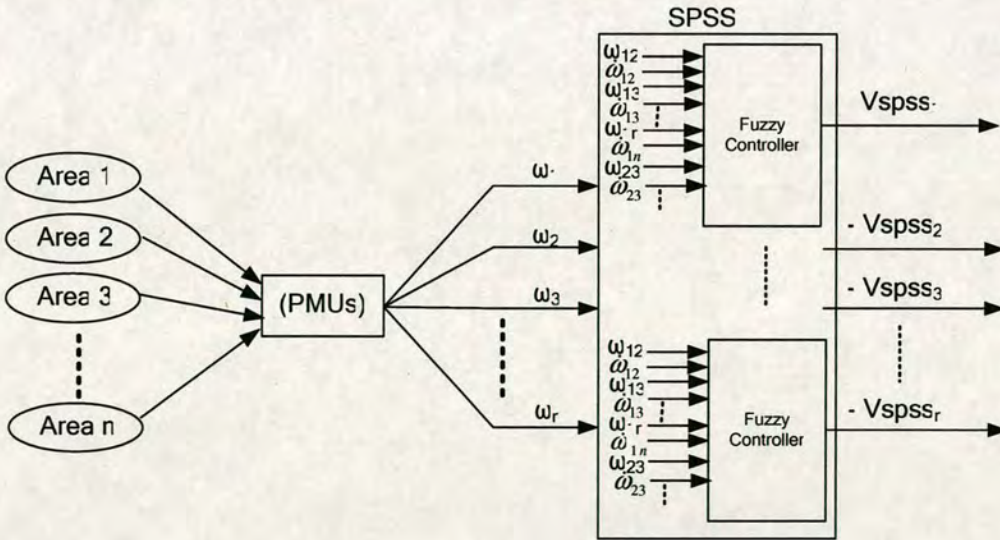


Figure 6.3 Type 2 SPSS general structure

of each two different areas involved is calculated as in the following equation:

$$\Delta\omega_{ij} = \Delta\omega_i - \Delta\omega_j \quad 6.2$$

where,

$\Delta\omega_i$: Average speed deviation of area i ($i = 1, 2, \dots, n$),

$\Delta\omega_j$: Average speed deviation of area j ($j = 1, 2, \dots, n$), and

$\Delta\omega_i \neq \Delta\omega_j$.

The process is repeated until each pair of the areas involved is covered. Both $\Delta\omega_{ij}$ and its acceleration signal are introduced as inputs to each fuzzy controller within SPSS as shown in Fig. 6.3.

There will be as many inputs to each fuzzy controller within the SPSS as there are numbers of pairs of average speed deviation differences and their derivatives (i.e. $\Delta\omega_{12}, \Delta\dot{\omega}_{12}, \omega_{13}, \Delta\dot{\omega}_{13}, \Delta\omega_{1n}$, etc.). For example, for the 3-area 6-machine power system shown in Figure 6.4 assuming that all the generators within each area are equipped with an IEEE type exciter, the average speed of each area (area 1 to area 3) is determined. The next step is to take the difference between the average speed deviations of every two different areas and their derivative in the 3-area 6-machine test system (i.e. $\Delta\omega_{12}, \Delta\dot{\omega}_{12}, \Delta\omega_{13}, \Delta\dot{\omega}_{13}, \Delta\omega_{23}, \Delta\dot{\omega}_{23}$).

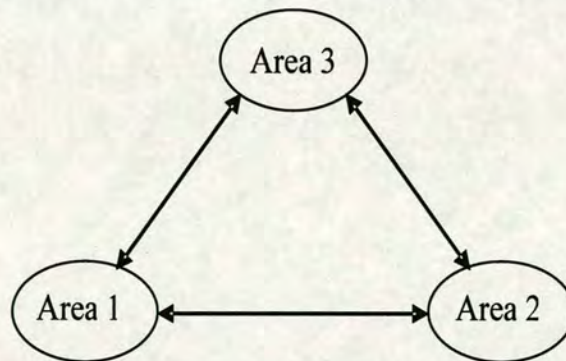


Figure 6.4 3-Area 6-machine power system

These six values representing average speed deviation differences and their derivatives will be injected as inputs for each fuzzy controller within the SPSS as shown in Figure 6.3. The SPSS will evaluate the inputs simultaneously according to the general control rules shown in the decision table 6.1 later on; whereas, the general description of the rules are given in Appendix B. Although all the inputs are injected to each fuzzy controller within the SPSS, a

fuzzy controller that is responsible to generate a stabilizing signal V_{spss_i} for the i th area will only evaluate the inputs that are related to the i th area; whereas, any input that is not related to the i th area is not evaluated. For example, a fuzzy rule evaluated by the fuzzy controller responsible to produce a stabilizing signal for area 1 (V_{spss_1}) within type 2 SPSS applied to the 3-area 6 machine model is:

Rule 1: If ($\Delta\omega_{12}$ is NB AND $\frac{d\Delta\omega_{12}}{dt}$ is NB) OR ($\Delta\omega_{13}$ is NB AND $\frac{d\Delta\omega_{13}}{dt}$ is NB)
THEN V_{spss} is NB.

where,

$\Delta\omega_{12}$: Average speed deviation difference between average speed deviation of area 1 and area 2.

$\Delta\omega_{13}$: Average speed deviation difference between average speed deviation of area 2 and area 3.

So as soon as the inputs are evaluated properly, the proposed supervisory power system stabilizer will produce stabilizing signals each of which is introduced to its proper area: the i th stabilizing signal, V_{spss_i} , generated from the fuzzy-based SPSS will only be applied to excitation systems of the synchronous generators, as in Fig. 6.2, that are contributing to the calculation of the average speed deviation of the i th area.

For all the tests systems considered in this thesis, area 1 is always assumed to be as the reference area with respect to the rest of areas on the basis the slack node assumed in the calculation of the power flow in MATLAB/SIMULINK is connected to G1 which belongs to area 1. This proposed design suffers a limitation; that is, the inputs to the SPSS as explained depends on the average speed of synchronous generators in each area. Hence, if the system configuration of the multi-machine model remains unchanged during load increase/change for example, the coherent group boundaries or region boundaries remain unchanged. In other words, the same groups of synchronous generators in multi-machine model are still within their original

regions prior to any power generation change for example. However, if the system configuration is changed (i.e. a synchronous generator or generators become part of a new region), the boundaries of the new regions must be clearly defined to appropriately determine the average speeds of the new regions so that the inputs to the SPSS must be updated accordingly. This process must be performed every time new region boundaries are formed which we consider it to be a shortcoming of this design unlike Type 1.

6.3.3 Type 3 Fuzzy-Based Supervisory Power System Stabilizer

This section presents the proposed structural design of Type 3 supervisory power system stabilizer. Figure 6.5 illustrates an example of the general structure of Type 3 fuzzy-based SPSS applied to the 6-machine 3-area multi-machine test model.

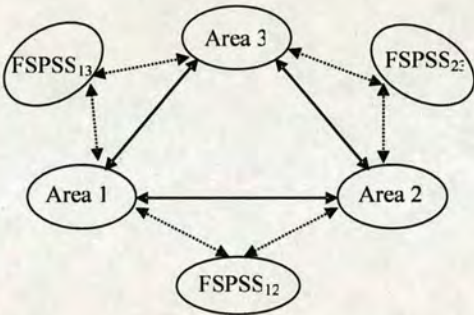


Figure 6.5 General structure of type 3 Fuzzy-based supervisory power system stabilizer

When comparing the structure of Type 3 SPSS to the other proposed structures of Type 1 SPSS and Type 2 SPSS presented in the previous sections, there are some noticeable similarities and differences between them. For example, in Type 3 SPSS the number of fuzzy variables injected to each fuzzy controller within the fuzzy-based SPSS is equal to two as in the case of Type 1 SPSS. Whereas the similarity between Type 2 and Type 3 SPSS is that the first input variable to each controller in Type 3 SPSS is the difference between the average speed deviations of two different areas. And the second input variable is merely the derivative of the first signal as explained before. Figure 6.6 demonstrates Type 3 fuzzy-based supervisory power system stabilizer structure. Each stabilizing signal estimated by Type 3 fuzzy-based SPSS is

introduced in opposite signs to the two different areas whose average speed deviations are used to determine the input variables. For example, V_{spss12} in Figure 6.6 is only applied to area 1 and area 2 in opposite signs.

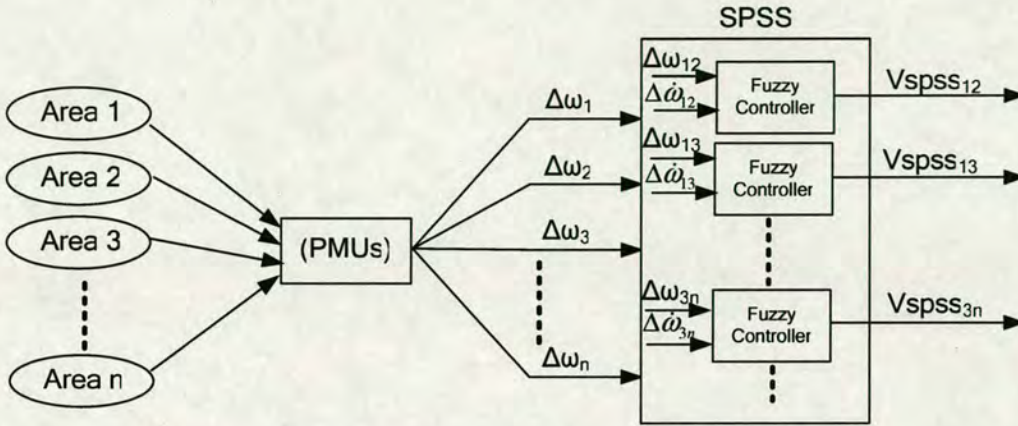


Figure 6.6 Type 3 Fuzzy-based supervisory power system stabilizer

The control rules that are used for Type 3 fuzzy-based SPSS are the same as control rules used previously for the other two types of SPSS, and they are shown in the decision table 6.1 in section 6.4 (general description is given in Appendix B). In addition, as in Type 2 SPSS it is possible that only some synchronous generators in the i th area (where $i = 1, 2, \dots, n$) contribute in the calculation of the average speed deviation of the i th area. For example, in the i th area there might be generating units to which no SPSS signals are going to be applied because they are equipped with manual excitations, and then their speeds are not taken into consideration when calculating the average of the i th area. Or it could be a complete area not influenced directly by SPSS like area 2 in the 16-machine 5-area test system: the synchronous generators in area 2 are all equipped with manual excitations; therefore, the average speed deviation of this area is not calculated and there will be no stabilizing signal introduced to the synchronous machines in this area since the stabilizing signals are always introduced to synchronous generators equipped with automatic excitation systems.

Based on the number of differences between average speed deviation of every two different areas, the proposed Type 3 SPSS will generate as many

stabilizing signals, V_{spss} , as the number of differences of average speed deviations as shown in Fig. 6.6. As an example, for the 3-area 6-machine test system the possible average speed deviation differences between areas are $\Delta\omega_{12}$, $\Delta\omega_{13}$, and $\Delta\omega_{23}$. Therefore, Type 3 SPSS will generate three different stabilizing signals V_{spss12} , V_{spss13} , and V_{spss23} each of which will be introduced in opposite signs to the proper areas (i.e. V_{spss12} is applied to area 1 and 2 only).

Through the analysis and research performed on this proposed structure, it is noticed that the damping of electromechanical oscillations are improved by Type 3 SPSS when the stabilizing signals corresponding to the reference area are not injected to the generators in the reference area. This is one of the limitations and drawbacks of this design which seems that its performance deteriorates as a result of high SPSS output range, and this deterioration in performance could have an adverse affect on the dynamic response of the system rather positive outcome. It should be mentioned that in all our three test models, area 1 is assumed to be the reference area.

Another limitation this proposed design suffers is again in relation to the coherent group boundaries. As stated before, the inputs to the fuzzy-based SPSS depend on the difference of the average speed deviations of every two different areas. If the system configuration (i.e. regions/area boundaries) of the multi-machine model remains unchanged during load increase/change for example, the average speed deviation of each area remains unchanged as well since the coherent group boundaries or region boundaries are still the same. In other words, the same groups of synchronous generators in multi-machine model are still contained within their original regions prior to any changes in the system. However, if the system configuration is changed (i.e. a synchronous generator or generators become part of a new region), the boundaries of the new regions must be clearly defined to determine average speeds of the new region, and the inputs to the SPSS must be updated accordingly. This process must be performed and repeated every time new

region boundaries are formed which is considered to be a shortcoming of this design unlike Type 1.

Based on research and observations of the three different proposed types of fuzzy-based supervisory power system stabilizers, Type 1 SPSS seems to provide the better improvement in damping of inter-area oscillations as the results will show in the subsequent chapter. In addition, it is not necessary to define the coherent group boundaries for Type 1 as in the designs of Type 2 and Type 3 because for Type 1 boundaries of regions have no influence at all on the design structure.

6.4 Fuzzy Control Rules Used for SPSS

The aim of this section is to present the design process and derivation of fuzzy control rules that are applied to the various types of supervisory PSS proposed. The first step in the proposed approach is to measure the shaft speed deviation of a synchronous generator. However, any fuzzy-based controller requires at minimum two input signals; therefore, the second proposed signal which in general can be taken as an input to the controller is the variation or derivative of the first input signal.

The derivative of the speed deviation is obtained through an approximate derivative block of transfer function as shown in Fig. 6.7. But in this thesis, MATLAB/SIMULINK is used to simulate and model synchronous generators and power systems, the speed deviation can be easily obtained from the SIMULINK model.

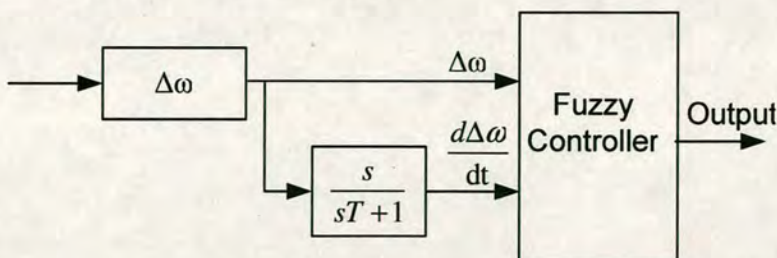


Figure 6.7 Speed Measuring in MATLAB/SIMULINK

In Fig. 6.7, $\Delta\omega$ represents the swing equation in the dynamic model of the synchronous generator and T is very small time constant found empirically (i.e. 0.03 sec). Two inputs shown in the figure are introduced as inputs to the fuzzy controller to produce the defuzzified damping signal.

Once the tools are determined to measure the speed deviation and to obtain its derivative/variation (acceleration signal), the fuzzy control rules can be derived based on the observation of the time response of the speed deviation and its derivative and also on the knowledge and behaviour of power system stabilizers. Although this is the general idea for single-machine infinite bus system, the same approach is applied to the base multi-machine system (2-area 4-machine model): first to observe the speed or speed deviation time response and its derivative of the benchmark power system model and then to derive and determine the proper actions that the fuzzy control rules must take to damp the electro-mechanical oscillations. And based on the reaction of the benchmark multi-machine model to the designed supervisory fuzzy controller, the control rules of this damping controller are applied and thoroughly tested on various and larger test systems. In each of the multi-machine model, it should be emphasized again that the signals are fetched globally; thus, the supervisory PSS can be also called a global damping controller.

For the multi-machine power system shown again for convenience, Fig. 6.8, a unit step change disturbance is applied to the system to determine the maximum and minimum of $\Delta\omega$ and $\Delta\dot{\omega}$. As for the inputs, since we are dealing with a multi-region model and the emphasis in this thesis is to propose a supervisory controller, the speed deviation of each area involved and contributing to the SPSS inputs is averaged (for type 2 SPSS and type 3 SPSS) assuming the generators in such area swing coherently as stated before;

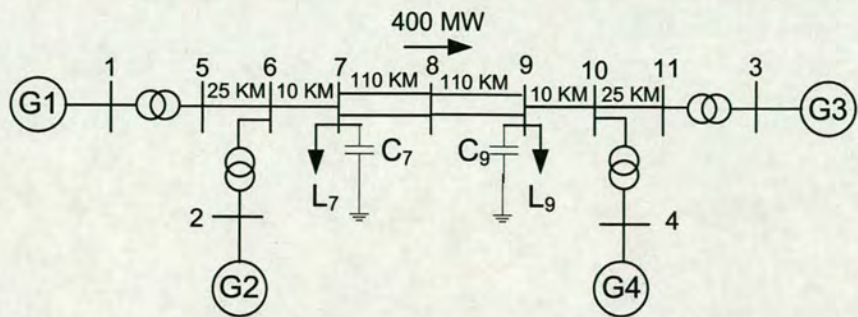


Figure 6.8 Line-diagram of 4-machine 2-area system

Once the proper input signals are determined, five fuzzy sets are specified for each input signal, and for each fuzzy set a linguistic variable is assigned. And they are NB (negative big), NM (negative medium), Z (zero), PM (positive medium), and finally PB (positive big). Figure 6.9 illustrates the speed and speed derivative with the five fuzzy sets specified for each input

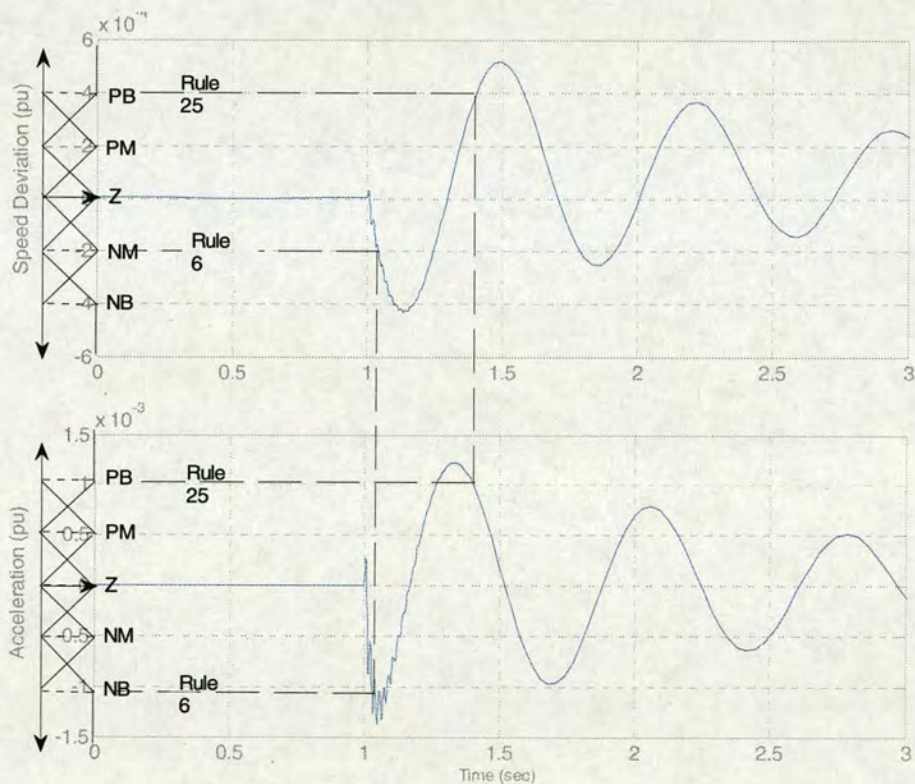


Figure 6.9 Speed deviation and speed deviation derivative

In this thesis, triangular membership functions are used to define the degree of membership. And the width of each membership function is chosen based on engineering judgment; however, as the width of a membership function is

made narrower, the sensitivity of a fuzzy controller increases in return. Again, based on the observation of the time responses of the input signals and on prior knowledge of the action that must be taken to increase damping and reduce speed deviation, a set of fuzzy control rules which relate the input to the output are drawn.

The best way to demonstrate the proposed rules for the supervisory power system stabilizer is by the truth/decision table. Decision table, Table 6.1, shows 25 (5 x 5) fuzzy control rules that are used through out this thesis for the various proposed types of supervisory power system stabilizers applied to different test models to effectively increase damping of electro-mechanical oscillations in particular, inter-area oscillations.

$\frac{d\Delta\omega}{dt} \backslash \Delta\omega$	NB	NM	Z	PM	PB
NB	NB (1)	NB (2)	NM (3)	NM (4)	Z (5)
NM	NB (6)	NM (7)	NM (8)	Z (9)	PM (10)
Z	NM (11)	NM (12)	Z (13)	PM (14)	PM (15)
PM	NM (16)	Z (17)	PM (18)	PM (19)	PB (20)
PB	Z (21)	PM (22)	PM (23)	PB (24)	PB (25)

Table 6.1 Decision Table of General Control Rules

When deriving the control rules for a fuzzy controller, it is better to choose the maximum point of a fuzzy set than choosing a point that belongs to two fuzzy sets at the same time. The reason for this is first to guarantee that this point belongs fully to one fuzzy set and second to guarantee that the fuzzy controller takes the maximum action available which corresponds to this situation. For example, as shown in Fig. 6.9 to derive fuzzy control rule 6, maximum values that are taking place at the same time are approximately chosen for the fuzzy set NM and NB, respectively. And once the two points are specified for the two inputs, the proper action by the fuzzy controller is determined as mentioned before based on the observation of the two inputs.

In this circumstance, because the speed and its derivative are in decreasing direction, then from observation of action of local PSS and knowledge to reduce speed deviation decrease, the proposed contribution by the supervisory PSS should act to prevent further speed decrease (i.e. in this case it should decrease electrical torque by decreasing field voltage).

When looking at each row of the decision table, each rule is deduced based on the physical information, observation of input signals and engineering judgments. When the speed deviation is NB for example and the acceleration signal is changing course from NB to PB, each action taken by the fuzzy controller must be approximately in proportion to the changes in the system behaviour to increase damping and to bring the system to steady state in the first swing as much as possible. What this implies is that as the acceleration is changing from a decreasing to an increasing direction, the fuzzy controller must provide a damping signal that will increase the oscillation damping as the rotors starts to accelerate and to make sure the system is brought to steady-state.

Another extreme case is when the speed deviation is PB and acceleration signal is changing also from NB to PB. The action taken by the fuzzy controller must also be approximately in proportion to the behaviour of the input signals. As an example, for fuzzy control rule 25 shown in Fig. 6.9. the speed deviation and the acceleration signal are both PB which means that the speed deviation is large and the system exhibits weak damping; therefore, the action that must be taken by the supervisory PSS should be adequate enough to increase damping of oscillation modes and reduced speed deviations. As the acceleration changes from PB to NB, the control action is weakened.

The diagonal in the decision table usually but not always in fuzzy logic is taken to be zero which means the action to be taken is zero or close to zero. It also means that there are no combinations of points that belong to the two membership functions of the two inputs signals at the same time.

Figure 6.10 and Figure. 6.11 illustrate the membership functions of the input and output variables of the proposed fuzzy-based SPSS:

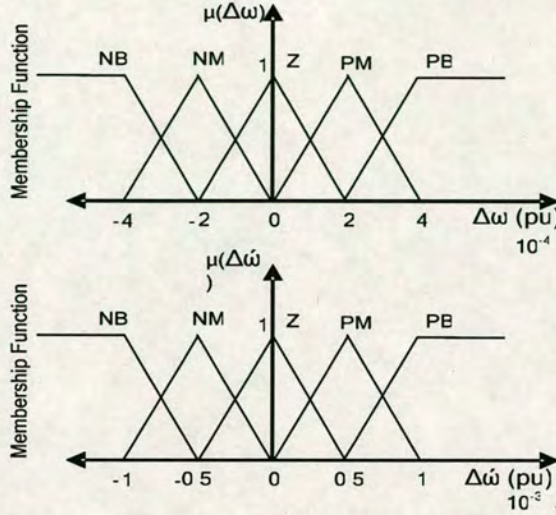


Figure 6.10 Membership Functions a) Speed deviation b) Acceleration

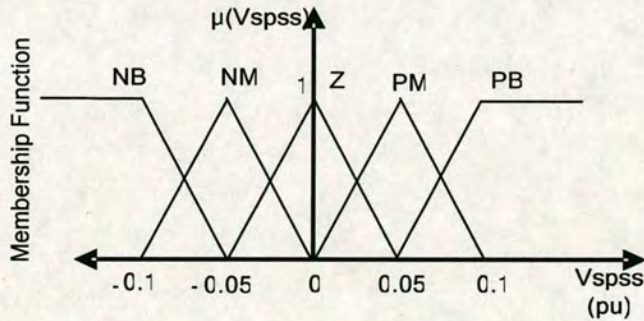


Figure 6.11 Membership Function of SPSS output

The universe of discourse (i.e. range) of the membership functions for each input is system dependent. It depends on the size of the system. The range has to be properly defined (tuned) so that the SPSS can provide proper damping; while, the universe of discourse of the SPSS output is independent and requires no tuning. Most of the proposed fuzzy logic controllers proposed in the literature depend on manual tuning of membership functions to establish the desired performance [9]. So is the case in the tuning of the membership functions proposed in this thesis.

The first thing that must be done to ensure proper range of membership functions is to observe the SPSS output which should have a decaying signal. The observation of the SPSS output should be done when there are no SPSS signals applied to the system (i.e. SPSS is present in the system but no SPSS signals are introduced to generators in other words). If the SPSS output signal takes a form other than a decaying signal assuming the system is going to steady-state after the disturbance, then this indicates that the range of the input membership functions must be retuned until a proper SPSS output signal or desired system performance is achieved. For example, Figure 6.12 and Figure 6.13 illustrate SPSS output signal for well-tuned and badly tuned input membership functions of the SPSS proposed.

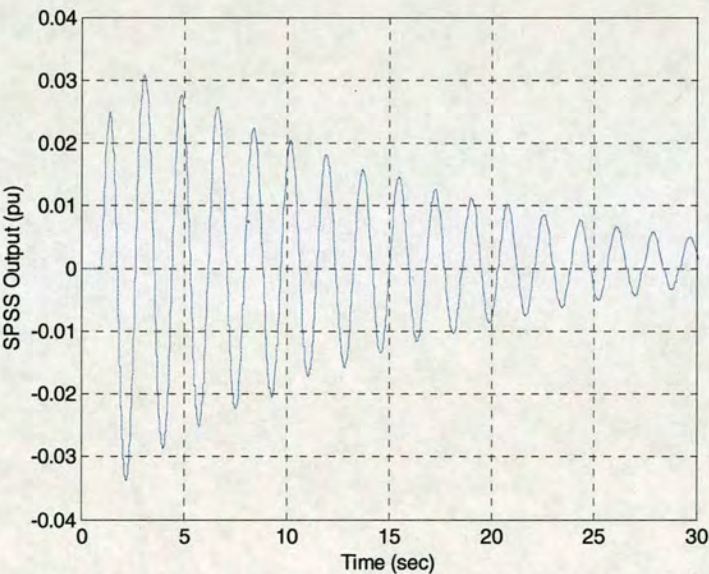


Figure 6.12 SPSS output signal with well-tuned membership functions

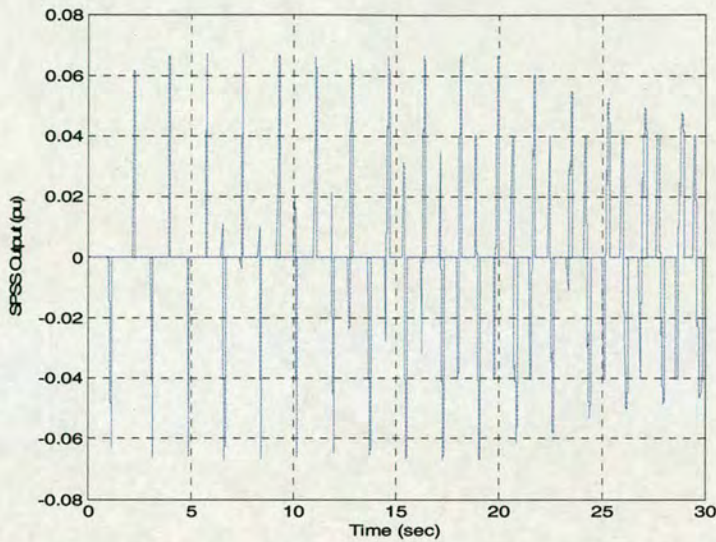


Figure 6.13 SPSS output signal with badly tuned membership functions

In such badly tuned fuzzy controller, the range of the membership functions must be retuned until proper decaying SPSS signal is reached. Unfortunately, this process of retuning must be performed manually and by trial-and-error which is a drawback of the proposed design.

Having established the control rules for such a system, in this thesis three different types of supervisory power system stabilizer implementations have been proposed. It cannot be emphasized enough that the uniqueness of each single SPSS design, applied to different test models, is that they all use the same control rules shown in Table 6.1 which can be described as general control rules as the simulation result in chapter 7 will prove the effectiveness and robustness of such designs.

6.5 Conclusion

With the availability of wide-area measurements, three various types of fuzzy-based supervisory power system stabilizers are presented and make use of such information to improve small-signal stability. Type 1 SPSS uses global speed deviation and its derivative between a reference generator and

ith generator; whereas, Type 2 SPSS and Type 3 SPSS use the difference between average speed deviations of areas and derivative as inputs to mitigate electro-mechanical oscillations. All the proposed fuzzy-based SPSSs use the same derived control rules. It is noted that region boundaries are irrelevant to the inputs of Type 1 SPSS. However, Type 2 SPSS and Type 3 SPSS inputs depend on the coherent group boundaries which are a drawback of proposed designs.

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Chapter 7

Testing of Supervisory Power System Stabilizer

7.1 Introduction

TIME domain simulations of nonlinear power system are quite often used to validate proposed controlled structures. The applicability and robustness of feedback controllers are examined to make sure the performance of the damping controllers are satisfactory when the power systems are exposed to small disturbances such as continuous changes in loads or power generations. And in order to demonstrate the effectiveness of the controllers, a comparison is carried out between the time responses prior and after the simulations of small-disturbances. In this chapter, the robustness and applicability of the proposed supervisory power system stabilizers using the same control rules and membership functions for each area in different power systems are demonstrated through time domain simulations and Prony analysis.

7.2 Prony Analysis

Prony analysis [1], in addition to the time response simulations, was carried out for the case studies presented in this chapter to demonstrate on the complex plane the shift of inter-area oscillation modes of the system and their associated damping and frequency. This will be a further confirmation of SPSS influence on the system's damping of electro-mechanical oscillations. But the main reason behind the use of Prony analysis rather than MATLAB to

obtain the eigenvalues/modes of the power system is that MATLAB from definition cannot calculate eigenvalues of fuzzy-based system since it is a highly non-linear system.

Prony analysis in nature analyzes the time response of non-linear model on a linear basis; whereas, linear analysis as the name indicates analyzes a linearized model around an operating point. However, when comparing the analysis of a linearized model around an operating point using the linear analysis to the analysis of non-linear model time response using Prony method, the overall picture of the system response is preserved (i.e. assurances that all critical modes are computed). And the differences between both methods are tolerable and justifiable. Table 7.1 gives a comparison between frequencies and decay time constant (τ) in seconds of electro-mechanical oscillation modes using linear analysis and Prony analysis for the system without SPSS when a unit step change of %0.05 is applied to voltage reference of G13 in the 16-machine 5-area system.

Linear Analysis		Prony Analysis	
Frequency (Hz)	τ (sec)	Frequency (Hz)	τ (sec)
0.11	1.16	0.19	2.22
0.15	3.45	0.4	4.55
0.42	50	0.42	16.94
0.52	6.67	0.51	7.14
0.61	6.67	0.61	5.26
0.71	1.82	0.7	2.04

Table 7.1 Comparison between linear analysis and Prony analysis

Further, Figure 7.1 demonstrates the oscillation modes on the complex planes for both analysis tools.

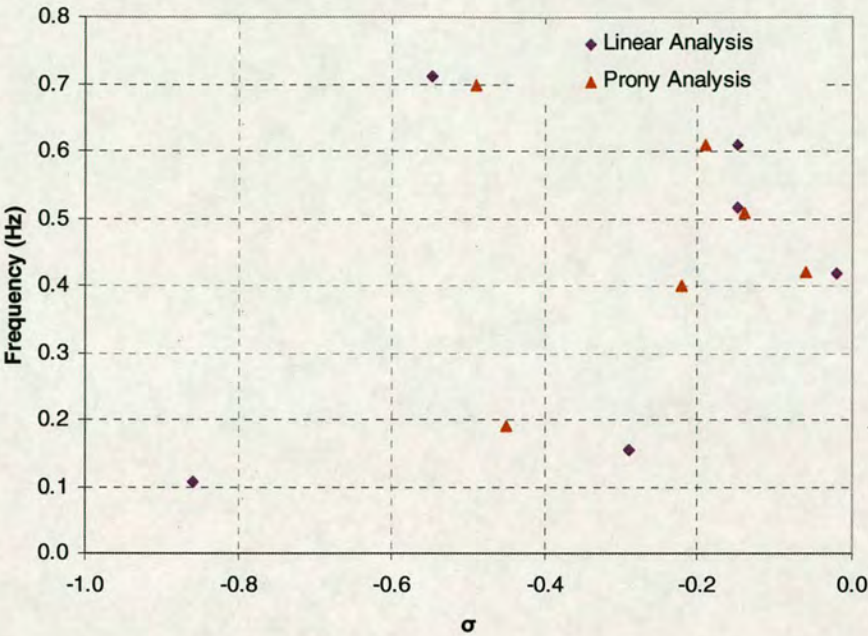


Figure 7.1 Oscillation modes computed by linear and Prony analyses

There are some differences in frequency and damping because normally Prony analysis of a non-linear time response of a system creates a time response that will be a sum of sinusoidal waves to best fit the non-linear response. In other words, if you have a wave response from non-linear model which is not sinusoidal, in Prony analysis the best fitting Prony time response that could be achieved for this non-linear time response would probably be in two, three, or 4, etc sinusoidal waves with slightly shifted frequencies or damping. Moreover, the fitting of non-linear model by linear model might also increase the number of modes that might not appear in linear analysis. However, most likely two modes computed by Prony analysis, for example, could be replaced by one mode in linear analysis. The end result is that Prony analysis as it is evident from Table 7.1 and Figure 7.1 could be dependable in computing the oscillations modes of the non-linear power system model.

7.3 Case Study: 3-Area 6-Machine Test System

The proposed supervisory power system stabilizer schemes are applied to the three different dynamic test models presented and described in chapter 5. However, only the simulation results and Prony analysis are presented in this chapter for some case studies in two test models, where the rest of the remaining simulation results for the dynamic test models and 2-area 4-machine test model are presented in Appendix C.

The test system considered first in this chapter is the 3-area 6-machine dynamic test model shown in Fig. 5.5. This small system is an expansion of the benchmark Kundur's model (i.e. 2-area 4-machine system). For this dynamic test model, only simulation results for Type 1 SPSS is presented in this section as the average speed of each area, required to be calculated for Type 2 SPSS and Type 3 SPSS, is so small since only two generators are in each area compared to the large test (16-machine 5-area test model). But further simulation results for all three SPSS types for this dynamic test model is presented in Appendix C as stated before.

To demonstrate the applicability of the proposed control rules and design structure of Type 1 SPSS, a line disconnection between bus no 7 and bus no 8 connecting area 1 and area 2 is applied for fault duration of 1.6 s. Figures 7.2 and 7.3 present the time responses of G2 and G5 with and without SPSS. Similar damping has been observed in the responses of the other generators but here and in subsequent sections, responses of some generators are shown.

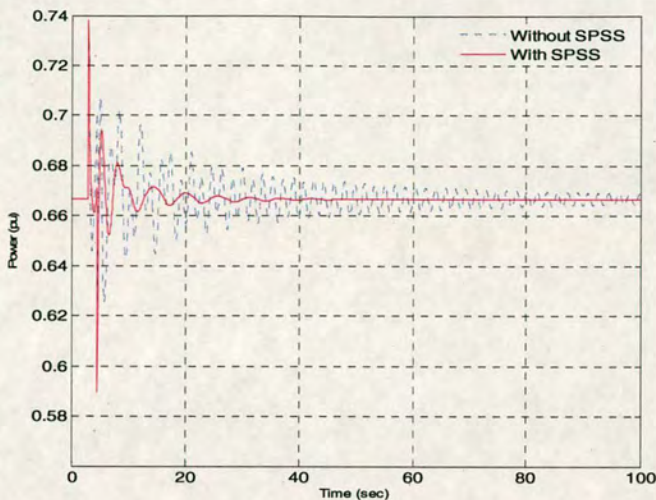


Figure 7.2 Dynamic response of G2 to line disconnection with and without
Type 1 SPSS

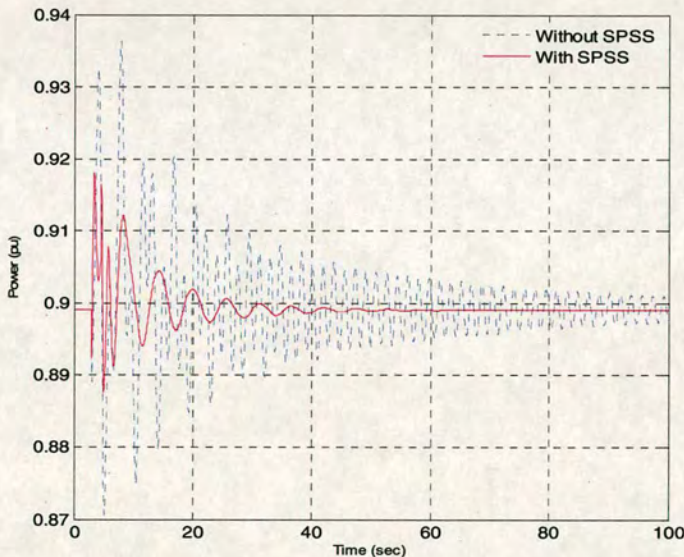


Figure 7.3 Dynamic response of G5 to line disconnection with and without
Type 1 SPSS

As it is clearly visible from the dynamic responses of some generators in the system, the supervisory PSS has improved the damping of the system. Furthermore, it stabilizes the system much quicker than without SPSS. Table 7.2 and Figures 7.4 and 7.5 obtained by Prony analysis illustrate the increase in damping of electro-mechanical oscillation modes when the SPSS is applied

to the system. Oscillation modes with and without SPSS are calculated using the same Prony analysis function, and because you are looking at the differences between the oscillation modes, systematic errors with Prony analysis would have no affect.

G2				G5			
Without SPSS		With SPSS		Without SPSS		With SPSS	
Freq (Hz)	τ (sec)	Freq (Hz)	τ (sec)	Freq (Hz)	τ (sec)	Freq (Hz)	τ (sec)
0.23	10.41	0.37	2	0.23	10.64	0.17	9.09
0.56	33.33	0.61	1.35	0.56	47.62	0.38	1.67
0.74	10.98	0.92	0.37	0.76	2.94	0.72	0.43

Table 7.2 Decay time contants and frequency of oscillation modes of G2 and G5 with and without Type 1 SPSS

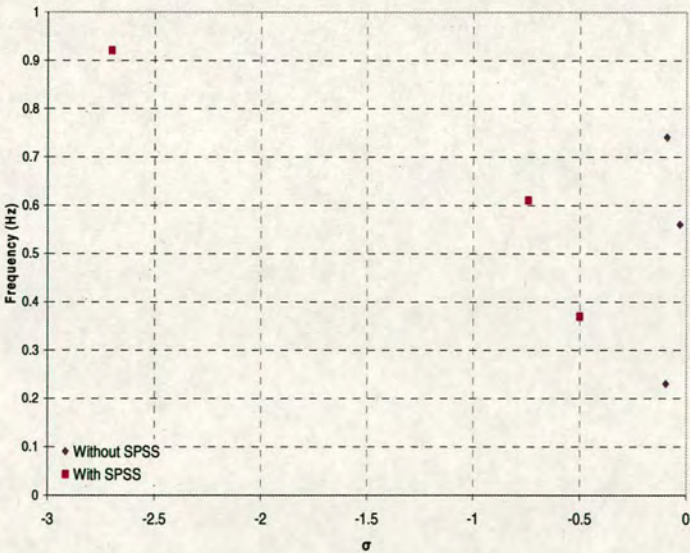


Figure 7.4 Oscillation modes Of G2 with and without Type 1 SPSS

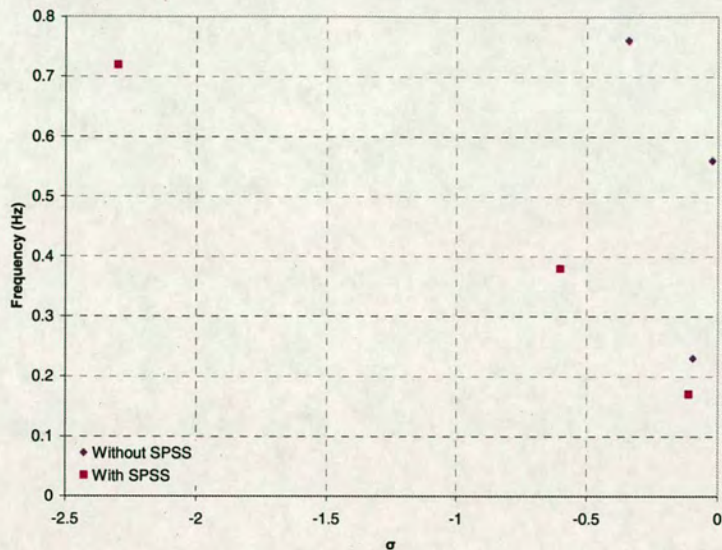


Figure 7.5 Oscillation modes of G5 with and without Type 1 PSS

The shifts of oscillation modes further to the left ensure that the stability margin is increased as well as the oscillation damping. Figures 7.6-7.8 illustrate the SPSS outputs for Type 1 SPSS, Type 2 SPSS and Type 3 SPSS, respectively. Further simulation results are in Appendix C which demonstrates simulation results of dynamic responses of this system.

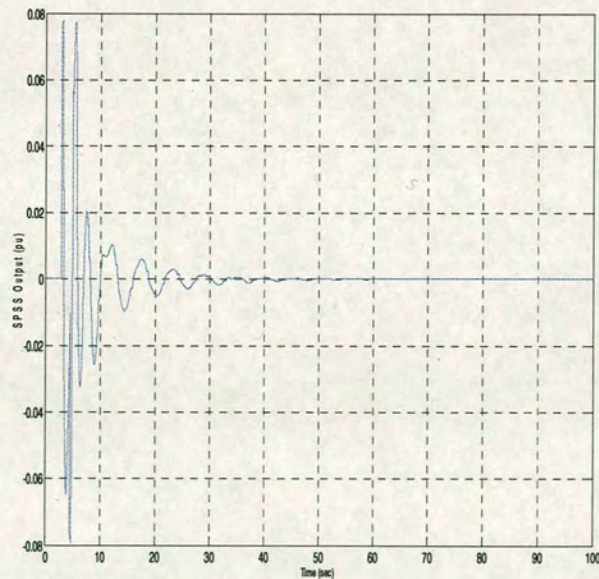


Figure 7.6 Type 1 SPSS output for G5

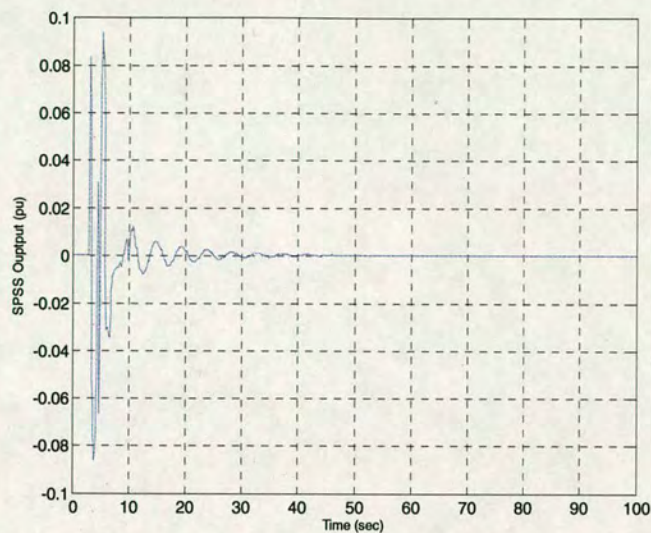


Figure 7.7 Type 2 SPSS output for G5

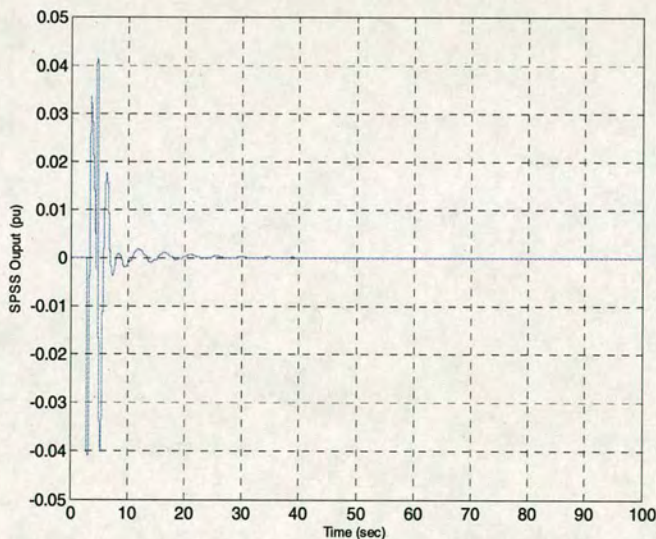


Figure 7.8 Type 3 SPSS output for G5

7.4 Case Study: 5-Area 16-Machine Test System

The test system considered in this section is the 16-machine 5-area dynamic test model shown in Fig. 5.6. This is a reduced order equivalent of the interconnected New England Test System (NETS) and New York power system (NYPS). The first nine machines (G1 to G9) represent simply the New

England Test System generation while the generating units (G10 to G13) represent the New York Power System. The remaining three synchronous machines G14 to G16 are the dynamic equivalents of the three neighbouring areas inter-connected to NYPS, and they are extremely large machines representing generator equivalents. As mentioned in chapter 5, the only local PSS is installed in G9. SPSS signals will be added to the rest of generators except generators in Area 2 in which the synchronous generators are manually excited. The static and dynamic data can be found in Appendix A.

7.4.1 SPSS Case Study

This subsection considers a case study to compare the dynamic responses of the system with Type 1 SPSS, Type 2 SPSS and Type 3 SPSS for the same fault. The comparison will demonstrate the effectiveness of Type 1 SPSS compared to other two proposed SPSS structures, Type 2 SPSS and Type 3 SPSS for reasons discussed later on. Through out the simulation studies either in this section and subsequent sections, it should be emphasized again that the same control rules shown in Table 6.1 and also in Appendix B is used for each dynamic test model, and the range membership functions of the inputs is shown in Figure 7.9.

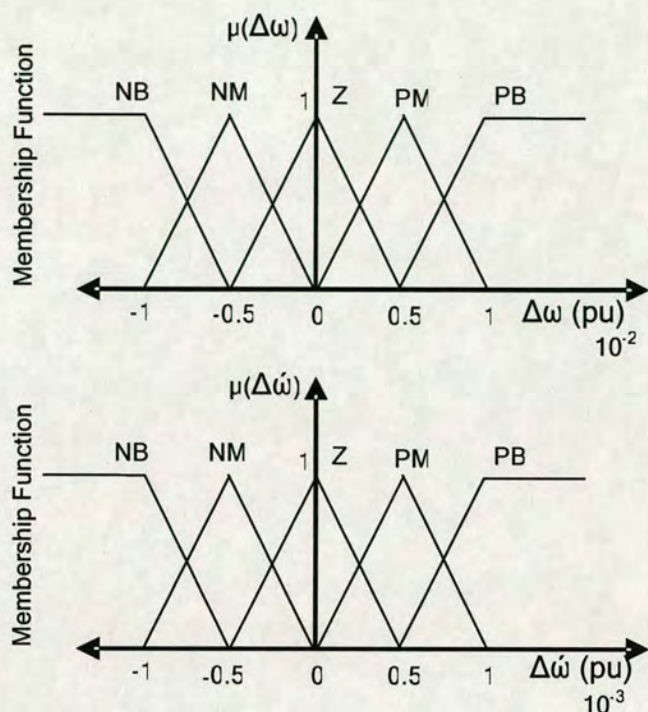


Figure 7.9 Membership Functions of SPSS inputs

The initial steady-state model described in Appendix A is disturbed with a three phase fault at bus number 60 for fault duration of 100 ms starting at simulation time equal to 3 seconds without assumption of time delay. All stabilizing signals generated from the supervisory power system stabilizers are injected according to the design structure of all three SPSS types without a loss of signal. For the purpose of demonstrating the robustness of the proposed control SPSS scheme, we will focus on some generators' responses in different areas for this case and for all subsequent cases. The dynamic responses of G14 and G15 with and without SPSS in the system for each SPSS types are shown in Figures 7.10 -7.15, respectively. While the comparison between system modes identified by Prony analysis is shown in Tables 7.3-7.4.

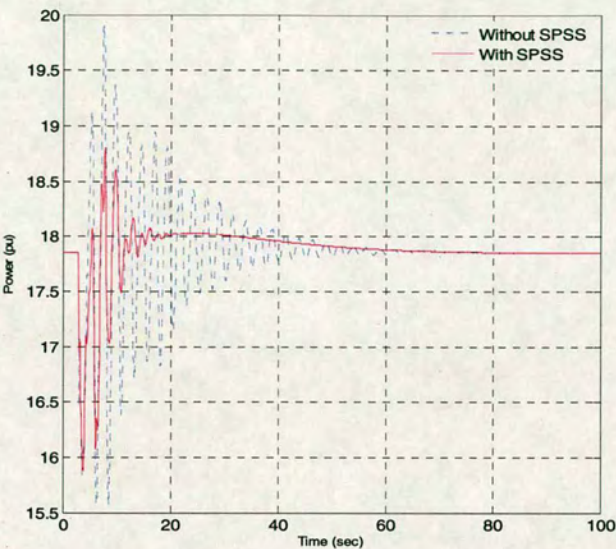


Figure 7.10 Comparison of G14 response to a short circuit with and without
Type 1 SPSS

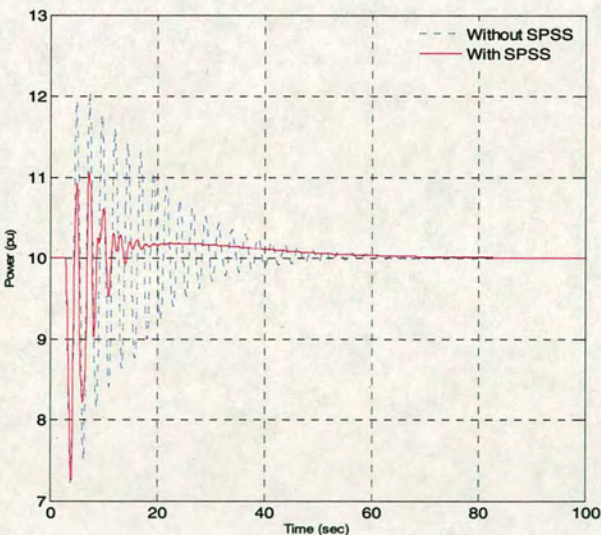
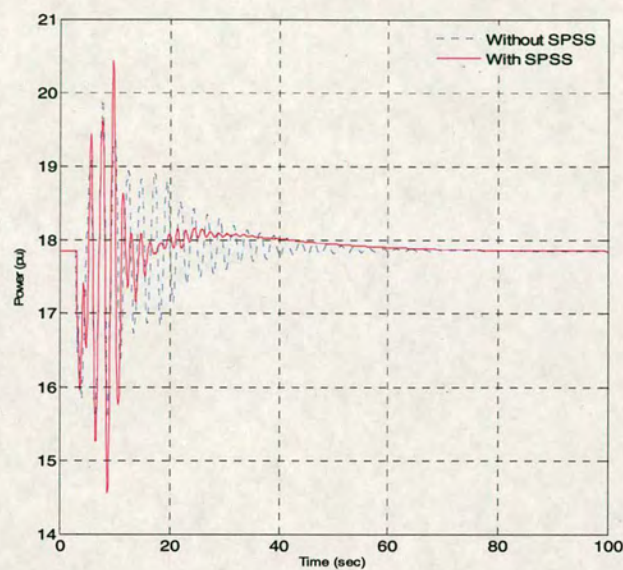
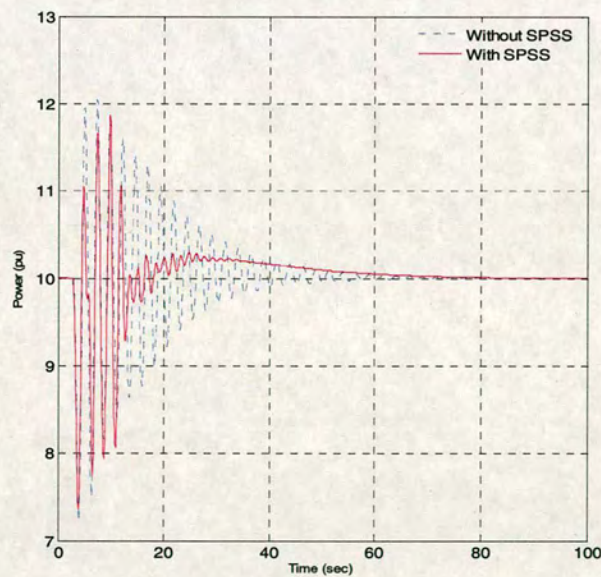


Figure 7.11 Comparison of G15 response to a short circuit with and without
Type 1 SPSS



**Figure 7.12 Comparison of G14 response to a short circuit with and without
Type 2 SPSS**



**Figure 7.13 Comparison of G15 response to a short circuit with and without
Type 2 SPSS**

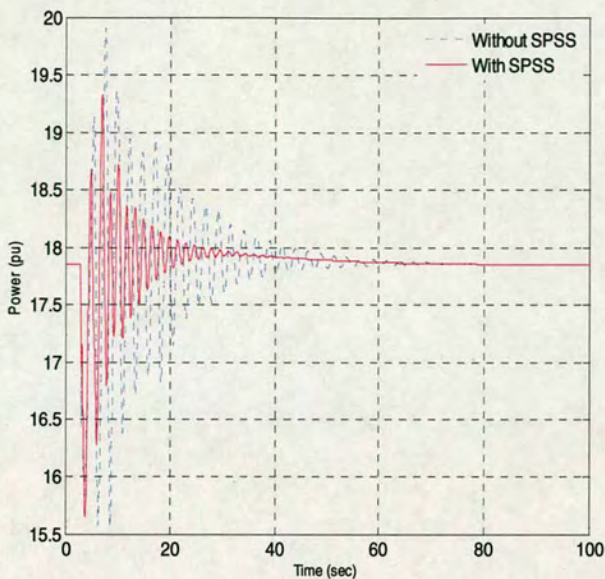


Figure 7.14 Comparison of G14 response to a short circuit with and without Type 3 SPSS

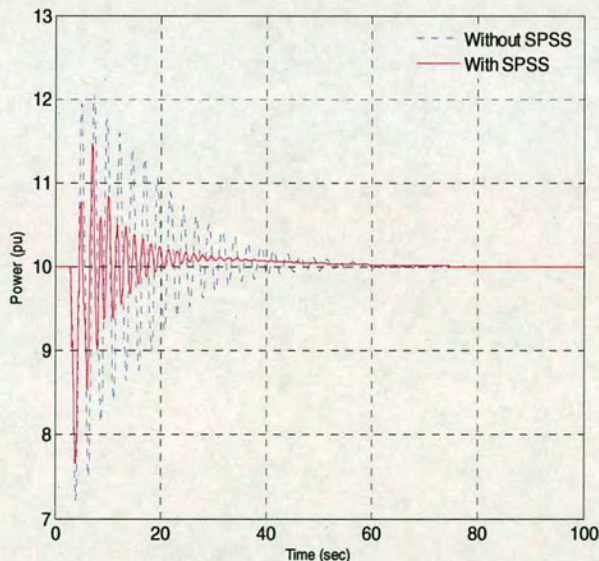


Figure 7.15 Comparison of G15 response to a short circuit with and without Type 3 SPSS

As can be seen from the dynamics responses, the system without SPSS is lightly damped and suffers low-frequency oscillations. But when the system is equipped with SPSS, the power system damping has been highly improved

compared to the system response without SPSS. Furthermore, when observing the time domain responses of the system with different SPSS types proposed, it is observed that Type 1 SPSS performs better than Type 2 and Type 3 SPSS. This might be due to the fact that the inputs to the Type 1 SPSS depend on speed differences between individual generators rather average speed differences between areas as in Type 2 and Type 3 SPSS. In a further analysis of time domain responses shown above, Tables 7.3-7.4 and Figures 7.16-7.21 obtained using Prony analysis for G14 and G15 demonstrate that the oscillation modes are shifted further to the left (i.e. increase stability margin) to ensure and increase small-signal stability

Modes without SPSS		Type 1 SPSS		Type 2 SPSS		Type 3 SPSS	
Freq. (Hz)	τ (sec)	Freq. (Hz)	τ (sec)	Freq. (Hz)	τ (sec)	Freq. (Hz)	τ (sec)
0.42	14.08	0.38	1.35	0.25	4	0.28	1.92
0.52	6.25	0.52	1.23	0.47	1.56	0.62	6.67
0.61	6.67	0.64	2.63	0.6	3.125	0.65	3.57
0.79	1.96	0.87	1.43	0.72	1.64	0.69	2.78
0.84	8.33						
0.91	1.51						

Table 7.3 Comparison of oscillation modes damping of G14 with Type 1 SPSS, Type 2 SPSS and Type 3 SPSS

Modes without SPSS		Type 1 SPSS		Type 2 SPSS		Type 3 SPSS	
Freq. (Hz)	τ (sec)	Freq. (Hz)	τ (sec)	Freq. (Hz)	τ (sec)	Freq. (Hz)	τ (sec)
0.14	1.89	0.33	1.25	0.28	5.26	0.29	1.92
0.38	12.66	0.48	1.02	0.43	2.70	0.36	1.02
0.42	14.29	0.64	1.89	0.53	2.04	0.62	7.14
0.47	3.85	0.66	2.38	0.61	5.26	0.65	3.57
0.61	3.85	0.85	1.00	0.93	2.77		
0.73	1.82						
0.84	8.34						

Table 7.4 Comparison of oscillation modes damping of G15 with Type 1 SPSS, Type 2 SPSS and Type 3 SPSS

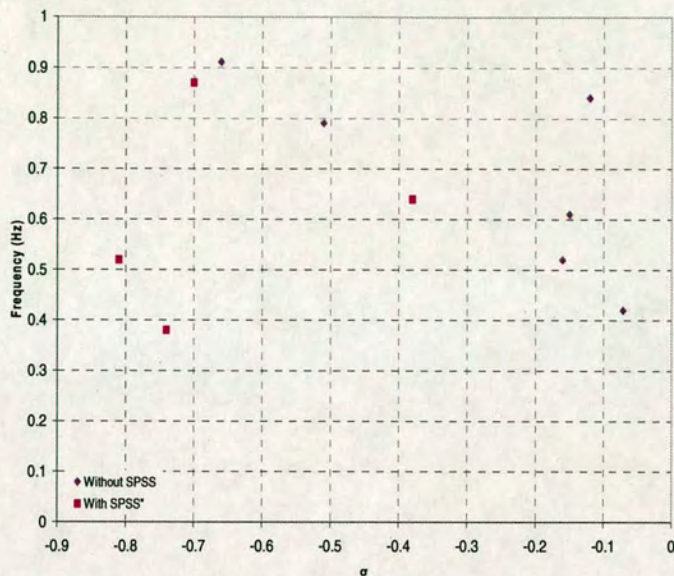


Figure 7.16 Oscillation modes of G14 to a short circuit with and without Type 1 SPSS

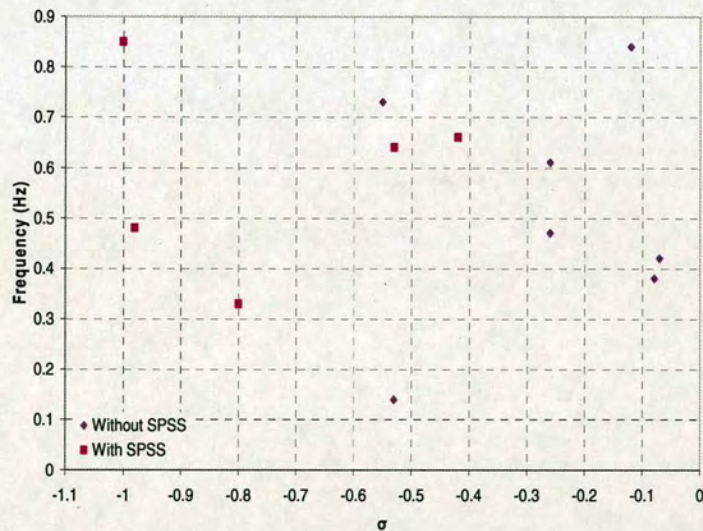


Figure 7.17 Oscillation modes of G15 to a short circuit with and without Type 1 SPSS

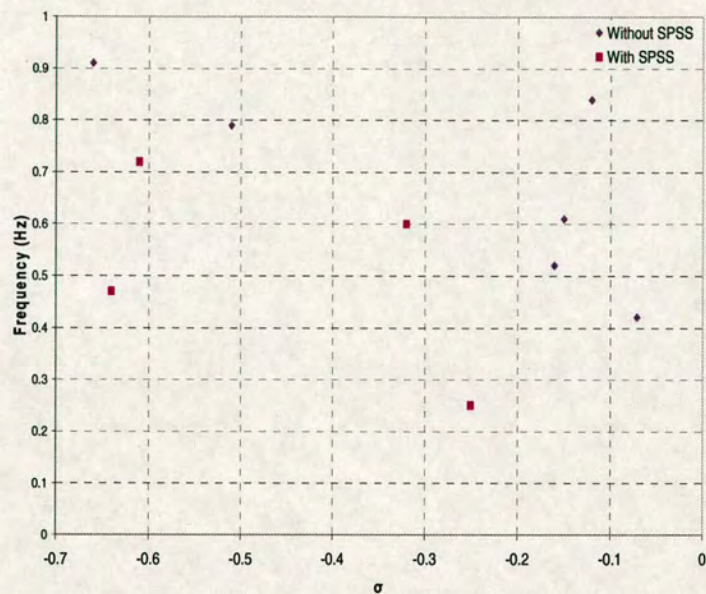


Figure 7.18 Oscillation modes of G14 to a short circuit with and without Type 2 SPSS

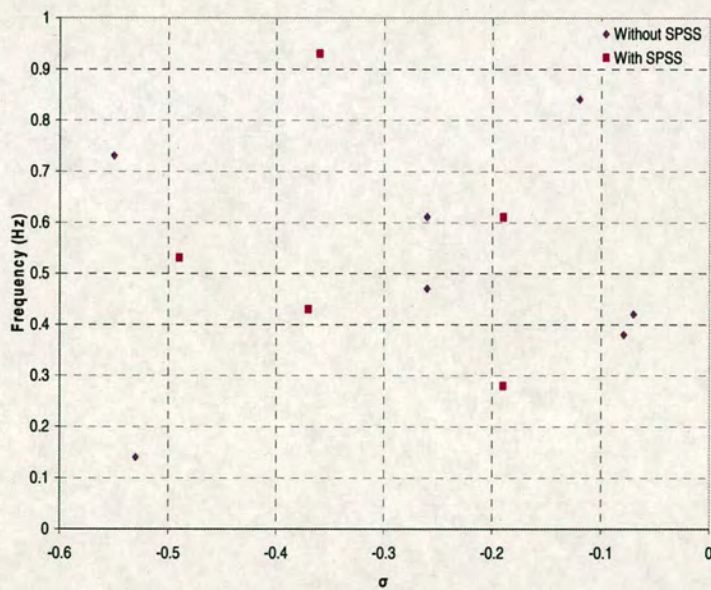


Figure 7.19 Oscillation modes of G15 to a short circuit with and without Type 2 SPSS

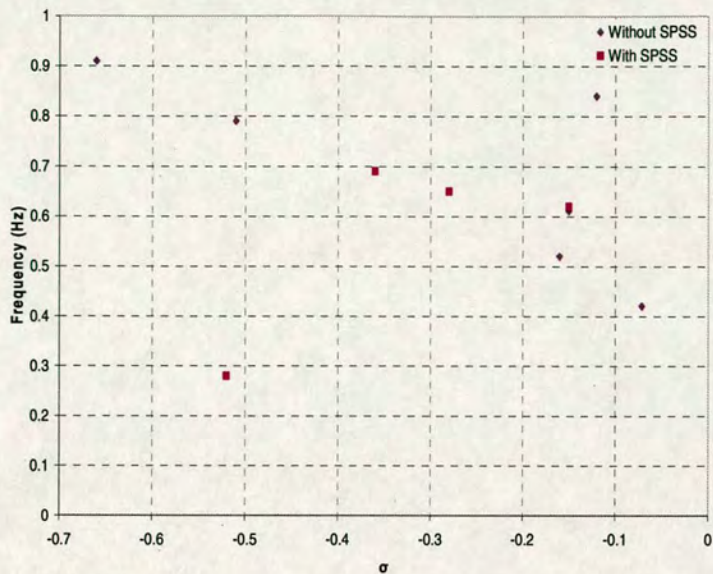


Figure 7.20 Oscillation modes of G14 to a short circuit with and without Type 3 SPSS

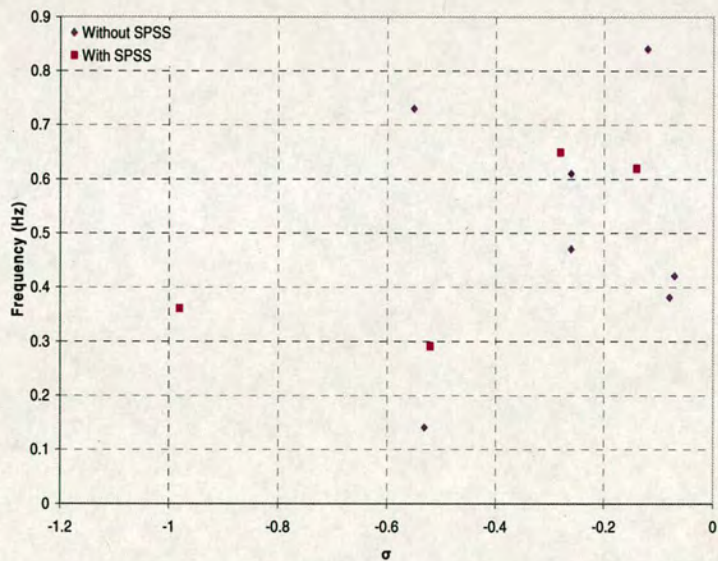


Figure 7.21 Oscillation modes of G15 to a short circuit with and without Type 3 SPSS

By observing the shifts of modes and the values of decaying time constants (or the damping constant on the plane) for the three SPSS types, we can clearly see Type 1 SPSS performs better than the other two SPSS types for reasons mentioned earlier. In the next subsection, we will explore more disturbances applied to the dynamic test model equipped with Type 1 SPSS.

7.4.2 Type 1 SPSS case Studies

This subsection considers further case studies that pertain to Type 1 SPSS control scheme which out performs other proposed SPSS controlled schemes. The first case presented here is the same as three phase short circuit presented earlier to demonstrate the indirect influence of Type 1 SPSS on some generators. Generators which are not equipped with stabilizing signals from the SPSS as in the case of synchronous generators (G10-G13) in Area 2 seem to be influenced indirectly by the SPSS. This is clearly visible for example in the dynamic response of G13 shown in Figure 7.22 which demonstrates the increase in damping of inter-area oscillations. In fact, this should be expected because if you place damping controllers on big generating units and there are small units, the small generating units are always affected by the big units.

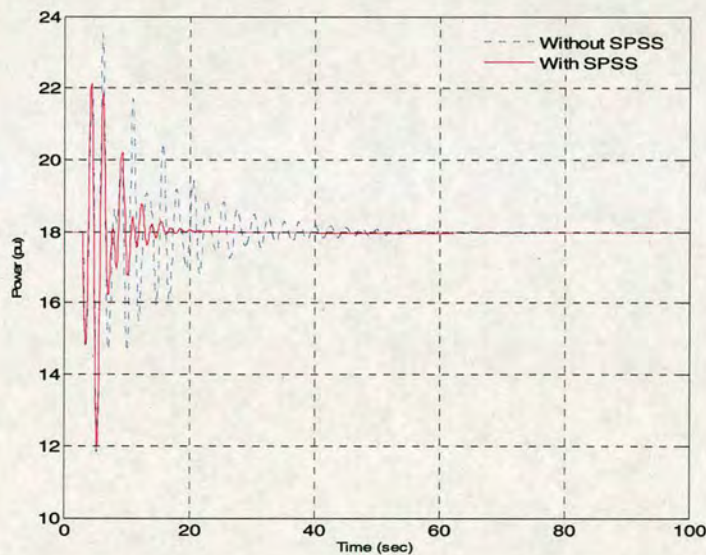


Figure 7.22 G13 response to a short-circuit with and without Type 1 SPSS in system

The analysis has so far treated fault case such as a short circuit To further evaluate the performance of SPSS, in the next case an outage of one of the parallel lines between bus numbers 53-54 for duration of 1.6 seconds (i.e. from simulation time $t = 3$ sec to $t = 4.6$ sec) is considered for simulations. The parallel lines are one of the major transmission corridors between NETS and NYPS regions of the dynamic test model. Therefore, taking one line out

would certainly put the system under severe stress to re-route the exchanged power during the fault time to meet load demand (i.e. weakens the system). Without any loss of SPSS signals, the dynamic responses of the system following the disturbance described are shown respectively in Figures 7.23-7.25 for G7, G14 and G15 located in separately geographical regions.

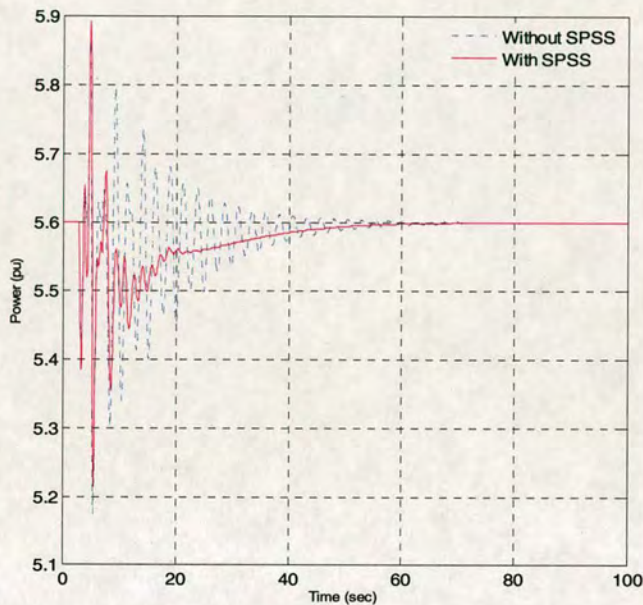


Figure 7.23 G7 response to a disconnection of line with and without Type 1 SPSS

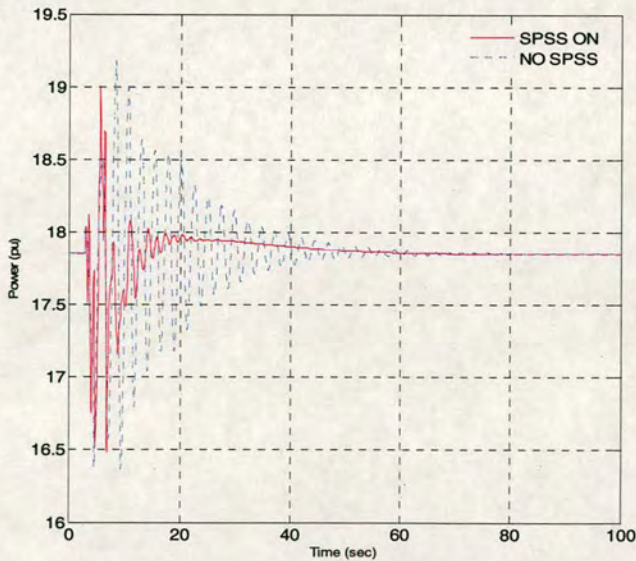


Figure 7.24 G14 response to line disconnection with and without Type 1SPSS

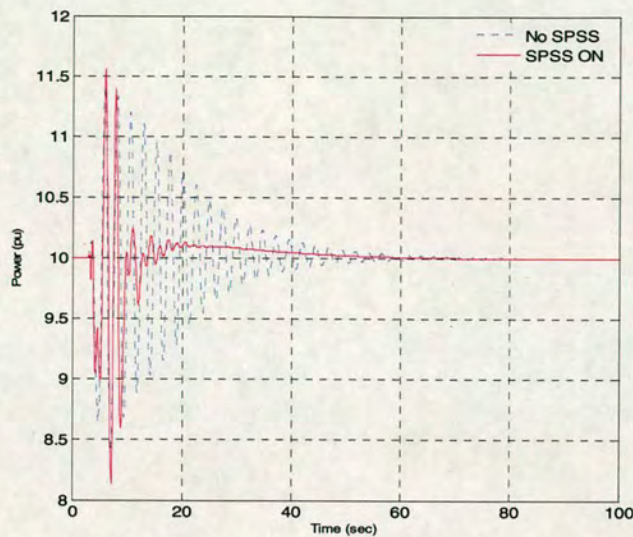


Figure 7.25 G15 response to line disconnection with and without Type 1 SPSS

As clearly visible from the figures, the system exhibits weakly damped oscillation modes without any effective damping controller present. However, again SPSS provides better damping as in the previous study cases compared to the system without SPSS. This ensures small-signal stability and will likely increase the safety and stability margin and allow more power transmissions. The dynamic responses of the system generators with and without SPSS are further confirmed with Prony analysis by Table 7.5 and Figures 7.26 to 7.28 corresponding to G13, G14 and G15, respectively. G13 is intentionally included to show the effectiveness of SPSS on regions not equipped with SPSS signals.

G13				G14				G15			
Without SPSS		With SPSS		Without SPSS		With SPSS		Without SPSS		With SPSS	
Freq. (Hz)	τ (sec)	Freq. (Hz)	τ (sec)	Freq. (Hz)	τ (sec)	Freq. (Hz)	τ (sec)	Freq. (Hz)	τ (sec)	Freq. (Hz)	τ (sec)
0.36	2.86	0.29	2.70	0.39	20.41	0.22	0.9	0.39	1.44	0.29	2.56
0.41	15.87	0.37	1.02	0.42	11.63	0.29	2.63	0.42	10.989	0.36	1.34
0.43	6.67	0.64	3.33	0.52	5.26	0.4	1.45	0.49	2.5	0.5	1.14
0.6	5.26	0.67	2.86	0.61	9.09	0.62	3.03	0.63	6.25	0.64	3.7
0.61	6.25			0.83	6.67			0.67	1.17		
0.95	2.32			0.83	2.44			0.83	9.09		

Table 7.5 Comparison of oscillation modes damping of G13, G14 and G15 without and with Type 1 SPSS

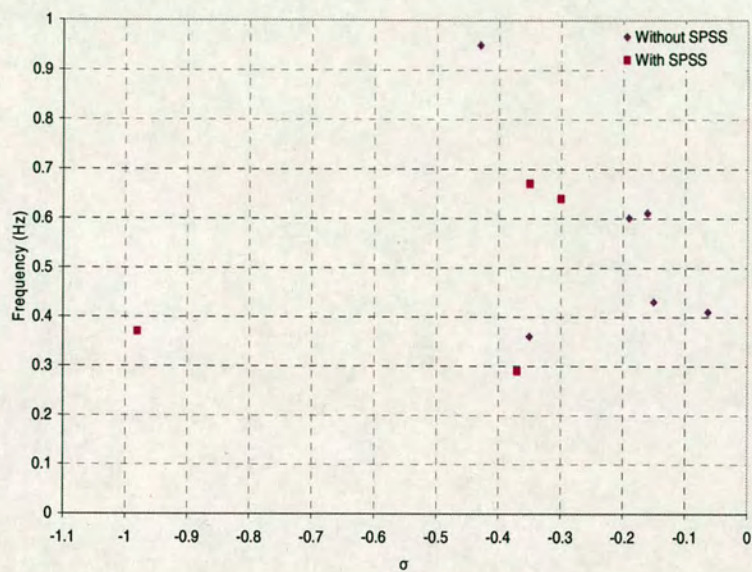


Figure 7.26 Oscillation modes computed by Prony analysis (G13) with Type 1 SPSS

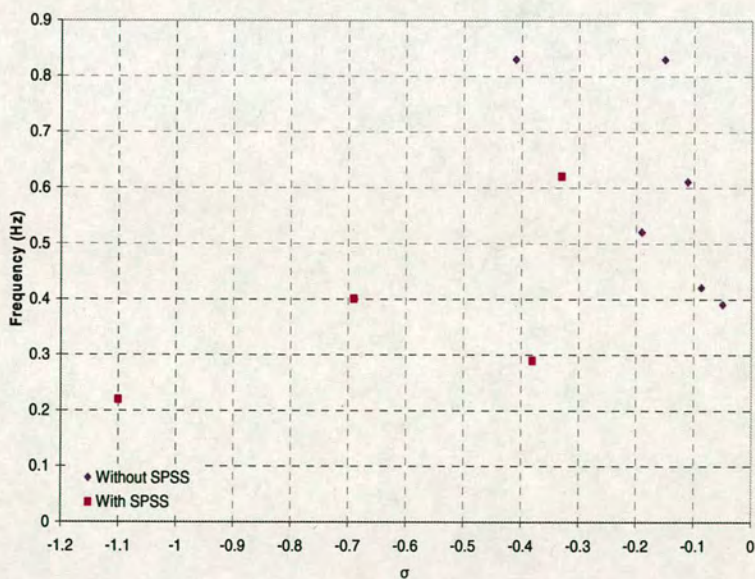


Figure 7.27 Oscillation modes computed by Prony analysis (G14) with Type 1 SPSS

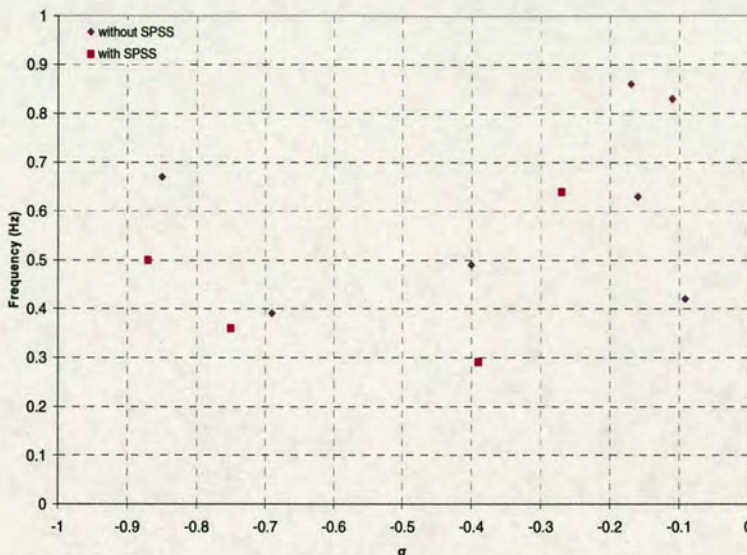


Figure 7.28 Oscillation modes computed by Prony analysis (G15) with Type 1 SPSS

From the figures, the rotor oscillation modes are clearly shifted further to the left which means that the damping of these oscillation modes has been highly improved. And this is visible especially with the inter-area oscillation of approximately 0.42 Hz associated with long decaying time constant when the system is without SPSS. However, when SPSS provides damping signals, this mode as well as other inter-area modes are effectively damped.

7.4.2.1 Influence of Time Delay

Since communication components are used to exchange data with SPSS, it is known from the literature that a long time delay might have detrimental consequences to the closed-loop stability and might neutralize the SPSS robustness to a lower level [2]. With recent technology of PMUs, the longest time delays that might happen between locations of PMUs to the control centre is 10 ms or less. Therefore, the next case is to further assess effectiveness of the SPSS with different time delays (i.e. 5 ms, 10 ms, 15 ms, 20 ms, etc) when the system is disturbed with an extreme case of two disturbances at the same time: a unit step change of %0.05 is applied to the

voltage reference of G16 and to the load reference of G1. Figure 7.29 and Figure 7.30 show the response of G16 with different time delays.

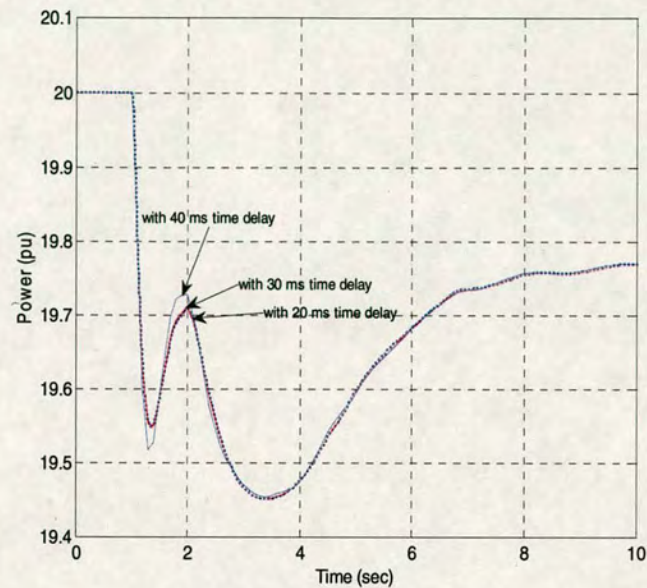


Figure 7.29 G16 response to a unit step change with different time delays

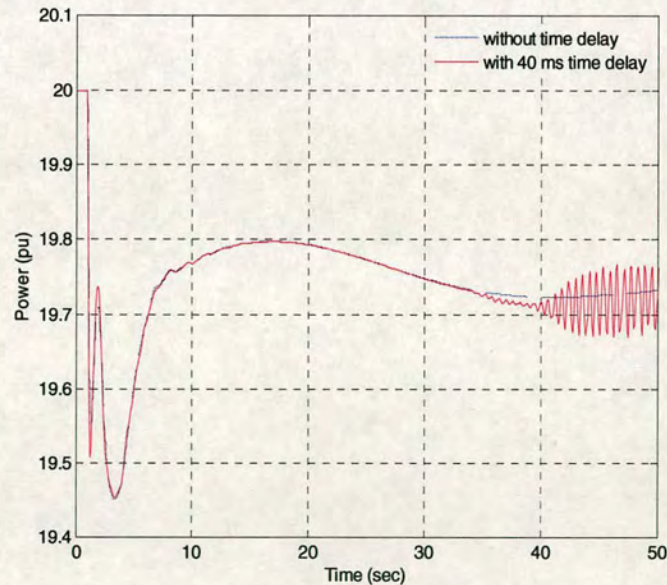


Figure 7.30 G16 response to a unit step change with 40 ms time delay

It is observed that the SPSS performance is satisfactory as long as the time delay does not exceed 30 ms. However, when the time delay is 40 ms, the system becomes unstable as clearly noticeable from Figure 7.30. And the

deterioration of SPSS performance to long time delays could be a subject for future works since the aim is to show applicability of SPSS.

In all the cases considered above, the simulation results show that SPSS has the ability to damp the power system oscillations, thus, increasing the small-signal stability. In Appendix C, there are further study cases and considerations such as loss of SPSS signals, sudden power generation reduction, etc to assess the robustness of Type 1 SPSS.

7.4.3 Type 2 SPSS Case Studies

We now consider case studies pertaining to type 2 control scheme illustrated in chapter 6 using the same control rules and membership functions as before. As mentioned previously, selected cases are examined to highlight the robustness and applicability for SPSS while different considerations for this control scheme as well as for other type control schemes are included in Appendix C.

For the first scenario, besides a disturbance consideration there will be an assumption that there is a loss of some SPSS signals that are injected to the excitation systems of synchronous generators and there is no time delay. The operating condition considered in the first case is a load generation reduction of G2 and G12 to 50% of their full-rated power at the initial-steady state while applying a unit step change of 0.05% to the voltage reference of G16 at $t = 1$ seconds. It is assumed that there is a complete loss of SPSS signals to Area 1 and Area 3 generators (which are chosen at random). Area 3 contains a large equivalent generator and usually big generating units have influence on smaller generating units or areas damping. The dynamic responses of the system following the prescribed operating condition with SPSS and without SPSS are shown in Figures 7.31 and 7.32 for G13 and G16, respectively.

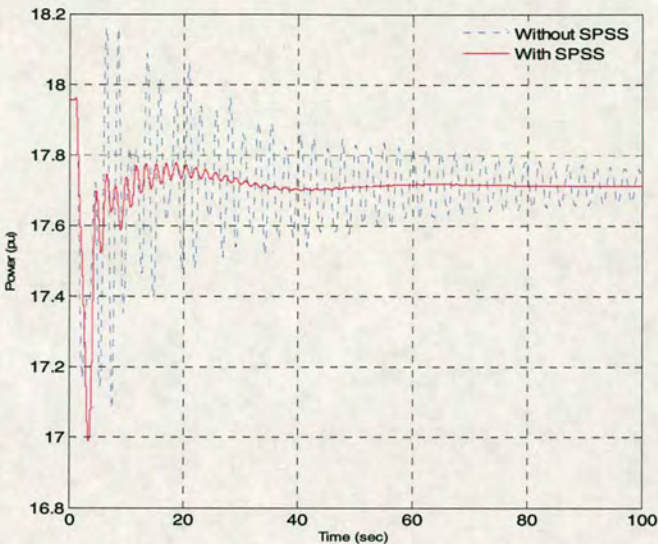


Figure 7.31 G13 response with and without Type 2 SPSS for MW variation

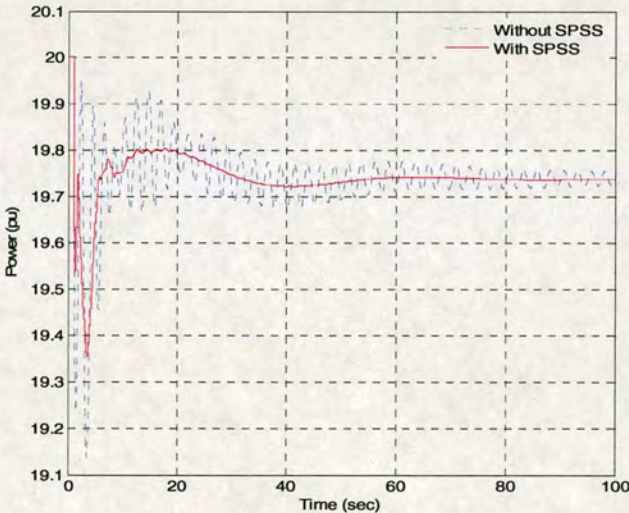


Figure 7.32 Response of G16 with and without Type 2 SPSS for MW variation

The comparison of the generators’ responses with and without SPSS clearly shows a significant improvement in system damping even when there is a loss of SPSS signals to some generators. Moreover, although G13 is not influenced directly by the supervisory power system stabilizer, its response shows a significant damping and indirect influence by the damping controller. To evaluate the performance of SPSS on the system response, Prony analysis is carried out for the system. Table 7.6 and Figures 7.33-7.34

provide a further confirmation of the significant damping by SPSS for the time responses of G13 and G16, respectively.

G13				G16			
Without SPSS		With SPSS		Without SPSS		With SPSS	
Freq. (Hz)	τ (sec)	Freq. (Hz)	τ (sec)	Freq. (Hz)	τ (sec)	Freq. (Hz)	τ (sec)
0.41	55.56	0.32	1.58	0.41	52.63	0.38	2
0.48	4	0.41	1.78	0.49	6.67	0.51	2.22
0.57	17.86	0.57	1.81	0.56	10.30	0.71	0.90
0.64	3.23			0.71	1.53	0.87	0.33
				0.83	15.38		
				0.86	3.22		

Table 7.6 Comparison of oscillation modes damping of G13 and G16 without and with Type 2 SPSS for MW variation

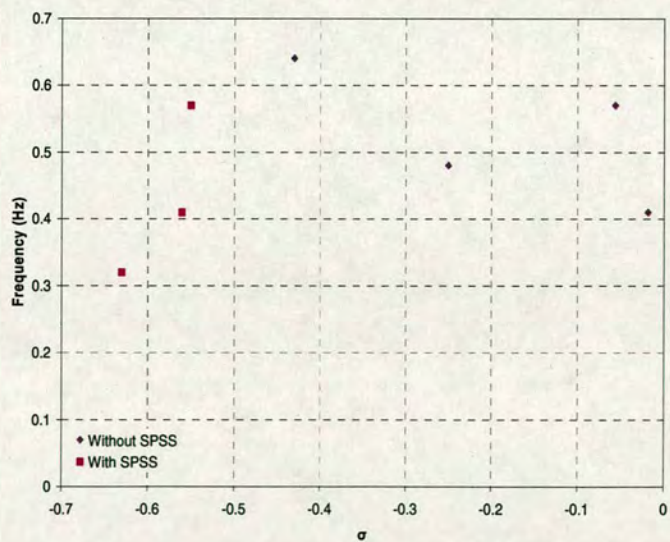


Figure 7.33 Prony analysis of G13 time domain simulation response for MW variation

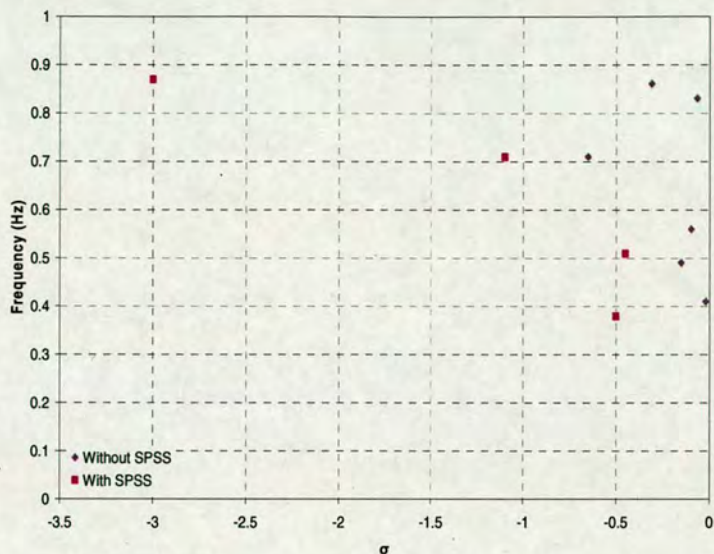
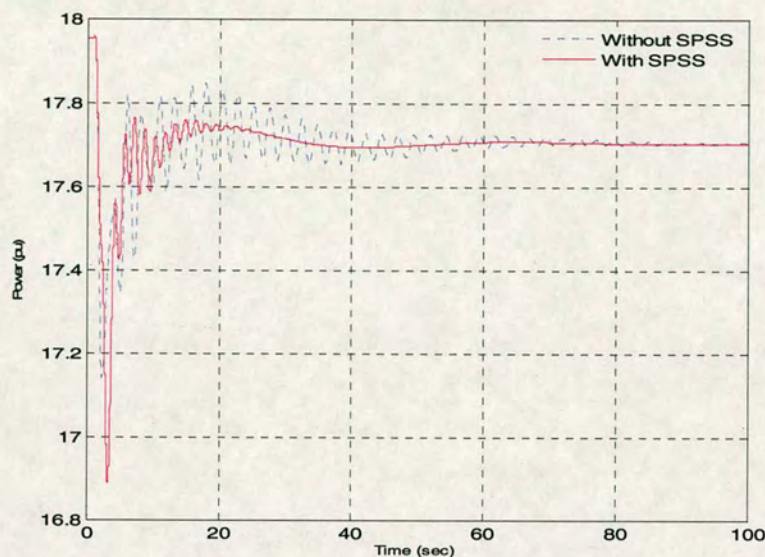


Figure 7.34 Prony analysis of G16 time domain simulation response for MW variation

Evidently, the Prony analysis results show that SPSS helps increase damping of inter-area oscillations and ensures small-signal stability. For example, there are two weakly damped modes 0.41 Hz and 0.57 Hz associated with long decaying time constants. With SPSS, the damping of these two modes has increased significantly as apparent from the figures and table.

In another and final study case of the proposed control scheme, Type 2 SPSS, presented in this section, the initial-steady state of the system considered is disturbed with 0.05% step change of voltage reference of G16, one of the large equivalent generating units, assuming all SPSS signals are intact. Figures 7.35 and 7.36 represent the dynamic responses of G13 and G16 to the disturbance applied, respectively.

Simulation results of G13 and G16 shown on next page reveal that system damping as in previous cases is enhanced compared when there exists no SPSS. And this is verified by performing Prony analysis on the simulation time response of G13 and G16. Table 7.7 and Figures 7.37-7.38 represent Prony analysis of time responses of G13 and G16, respectively.



7.35 Dynamic response of G13 to a step change with and without Type 2 SPSS

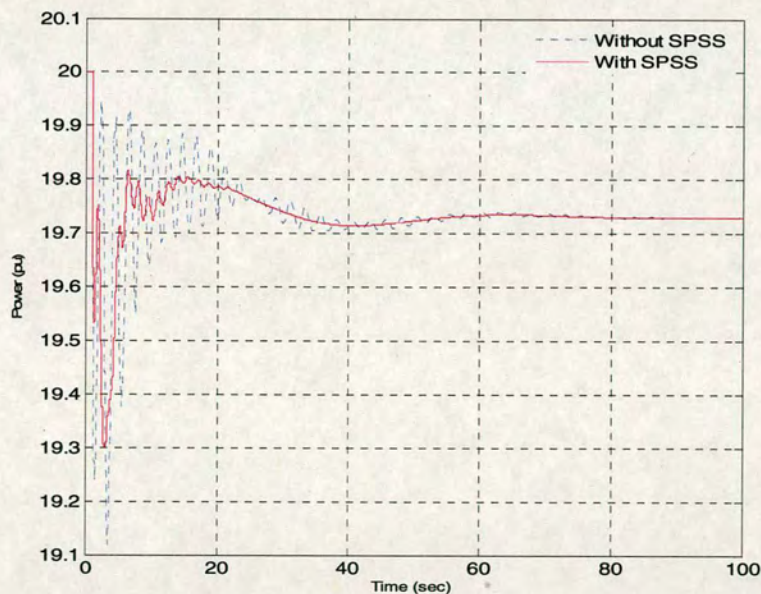


Figure 7.36 Dynamic response of G16 to a step change with and without Type 2 SPSS

G13				G16			
Without SPSS		With SPSS		Without SPSS		With SPSS	
Freq.	τ	Freq.	τ	Freq.	τ	Freq.	τ
(Hz)	(sec)	(Hz)	(sec)	(Hz)	(sec)	(Hz)	(sec)
0.42	27.03	0.16	2.70	0.42	25.641	0.14	1.96
0.49	8.33	0.38	2.22	0.43	1.09	0.27	1.39
0.51	1.53	0.42	2	0.49	7.69	0.46	3.34
0.62	7.69	0.49	3.125	0.57	3.45	0.59	1.25
0.67	1.49	0.63	3.03	0.89	2.86	0.63	2.70
1.1	1.06	0.65	1.53				

Table 7.7 Comparison of oscillation modes damping of G13 and G16 without and with Type 2 SPSS for step change disturbance

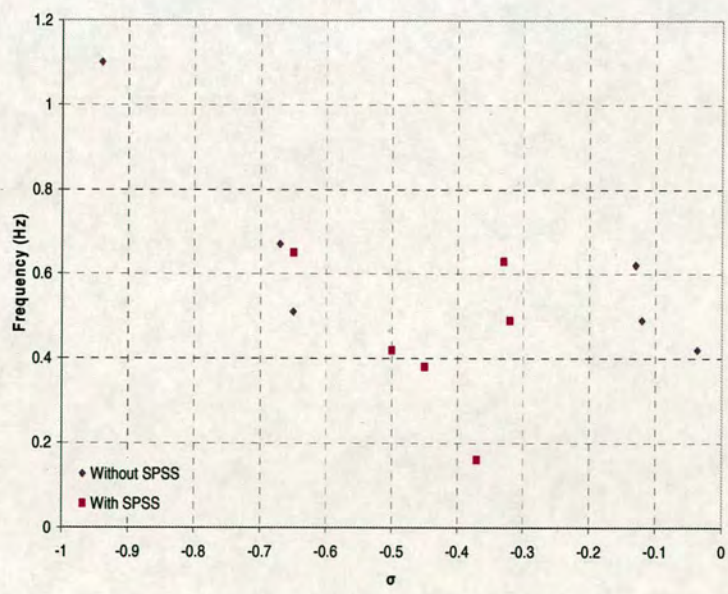


Figure 7.37 Prony analysis of time response of G13 to a step change disturbance with and without Type 2 SPSS

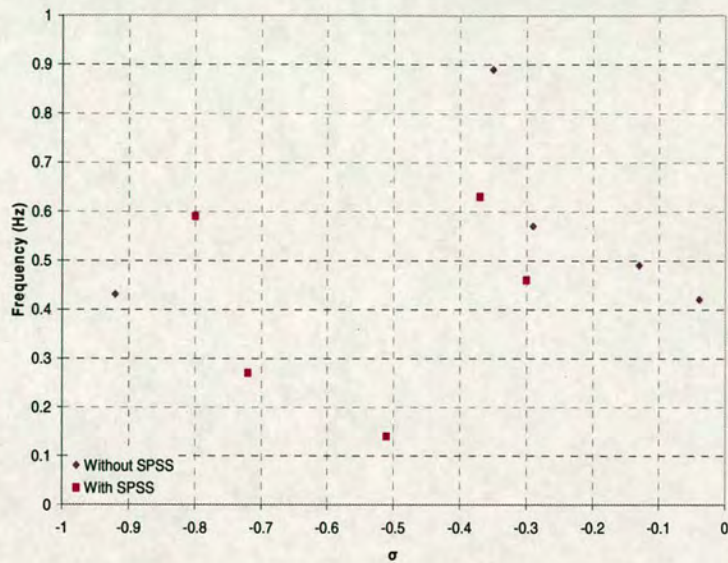


Figure 7.38 Prony analysis of time response of G16 to a step change disturbance with and without Type 2 SPSS

The Prony results reveal that SPSS provides better small-signal stability improvement in comparison when the system is without SPSS. This is visible with weakly damped inter-area mode with frequency of 0.42 as shown in the table and figures. When the SPSS is applied, stability margin is increased, thus, shifting the modes that are close to the stability boundary further to the left to ensure stable operation.

Further simulation results of disturbances such as power generating reductions, load reference, generator disconnection, etc applied to 16-machine 5-area test system as well as to other test systems explained in chapter 5 are included in Appendix C.

7.5 Conclusion

In this chapter, the central objective is to verify and assess the robustness and applicability of the proposed control structures illustrated in previous chapter using the same derived control rules and membership functions for each area in the power system. The validation of such robustness and applicability of

the different SPSS types is carried out through the time domain simulations of various types of disturbances applied to the non-linear 16-machine 5-area test system.

Simulation results presented in this chapter clearly show that the system response with any type of SPSS applied is better damped than without the SPSS. However, comparison of dynamic responses using different types proposed control structure indicated that Type 1 provides better damping performance than the other two SPSS types. This is most likely because with Type 1 the inputs to the fuzzy controller within SPSS do not depend on the difference of average speeds between two areas as explained in chapter 6. So it is less sensitive to changes in average speeds of areas. Moreover, the simulation results of system response to three phase short circuit indicate that Type 3 SPSS is more sensitive to losses of SPSS signals in comparison to the other two SPSS types. However, Type 3 SPSS still causes effective damping of inter-area oscillations when there is no loss of SPSS signals as illustrated in Appendix C. Further analysis of time responses using Prony analysis confirms that the proposed SPSS approaches increase stability margins of the power system, thus, ensuring small-signal stability especially if the system is continuously exposed to small disturbances because of changes in loads or power generations [3].

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Chapter 8

Conclusions and Suggestions for Future Works

8.1 Conclusions

S MALL signal stability problem has been a major concern for power system operators for a long time now since it could jeopardize the smooth operation of inter-connected multi-area power systems and threaten the stability and reliability of the power system. Therefore, it is not surprising that the problem of robust decentralized and centralized controller designs for large power systems has been an active research area for the last decades.

In this thesis, we are motivated to investigate more effective control schemes in order to ensure small-signal stability, hence, increase security and stability of large power systems. And in recent years, inter-area oscillations have been the main focus of study since local power system stabilizers cannot ensure effective damping of such modes all the time. And because it is known that inter-area oscillation modes typically have high observability and controllability in either the active power of tie line or speeds between areas involved in these inter-area oscillations, these two possible inputs could be used as any proposed controller's inputs to enhance system damping. With advancement of phasor measurement units (PMUs) technology to transmit information related to the power system status at a particular time, wide-area measurement or global information such as active tie-line power or speed between regions can be readily available to improve system damping in particular inter-area oscillation modes.

As shown in this thesis, different control design implementations which are based on fuzzy logic and rely on remote input signals (i.e. speeds from machines involved in the system) are proposed to enhance small-signal stability. The uniqueness about these three different supervisory power system stabilizers is that they all use the same general derived fuzzy control rules and membership functions for each area in different test models. Therefore, it is not necessary to optimize the fuzzy control rules and membership functions for each generator or area which is an optimistic trait of such designs.

Three power system models are used to validate the robustness and applicability of proposed Type 1 SPSS, Type 2 SPSS and Type 3 SPSS using the same general control rules and membership functions throughout. They have been applied to study models which exhibit electro-mechanical oscillations due to weak-ties and various disturbances. Time domain simulation results have shown that damping of electro-mechanical oscillations in particular inter-area oscillation modes has been enhanced by the application of SPSS and in some cases, oscillations are effectively damped. Thus, the power system is stabilized under proposed control strategy (i.e. same control rules based on fuzzy logic methodology). Further assessment of system dynamic response by prony analysis is conducted to confirm the robustness of SPSS by showing the shift of modes on the complex plane away from critical stability boundary (i.e. imaginary axis).

Based on the observation of the simulation results and structure of proposed SPSS, it is noted that Type 1 SPSS provides better damping performance and effectiveness in comparison with the other two types. Moreover, out of different SPSS designs Type 1 SPSS is highly recommended because the controller's inputs merely depend on the global speed difference between the reference generator and i th generator; whereas, the inputs to other SPSS controllers depend on the average speed difference between every two possible regions involved. Therefore in the case of average speed input

dependents the system configuration under different operating conditions must be known so that the SPSS inputs are properly calculated and updated to generate proper damping signals. This could be trouble some; however, in all our test models, the system configuration remains the same in all case studies. Another observed characteristics of SPSS types, damping performance by type 1 SPSS and type 2 SPSS seem to be less affected and less sensitive in comparison to type 3 SPSS when there is a loss of some SPSS signals, and this is apparent in the short circuit case study.

8.2 Suggestion for Future Works

Promising supervisory power system stabilizers using the same control rules and membership function have been presented in this thesis. The next step for some future work is

- To investigate more thoroughly communication delays and its influence on the system response.
- To extend the validation of SPSS types and time domain simulations of various disturbances to more detailed dynamic models and realistic systems.
- To investigate the proper locations of phasor measurement units (PMUs) and to incorporate this along with further research of how many and which generators are necessary to be influenced directly by SPSS since some generating units might not have major beneficial influence on the system damping.
- To investigate the performance of SPSS when the load types modeled are constant power or dynamic (i.e. induction motors).
- To investigate how to improve further Type 2 and Type 3 SPSS
- Further research should be related to more intelligent system (SPSS): system that can identify oscillations and act only when the oscillations

are too high (i.e. damping of inter-area modes is too small) or exceed the threshold. The system should define which signals should be used as inputs and where the outputs should be directed (to which generating units).

- And finally, the future work can be related to other techniques other than fuzzy logic.

Appendix A

A.1 16-Machine 5-Area Test System Data

Table A.1: Machine Bus Data

<i>Bus number</i>	<i>Voltage (p.u.)</i>	<i>Power generation (p.u.)</i>
1	1.0450	2.50
2	0.9800	5.45
3	0.9830	6.50
4	0.9970	6.32
5	1.0110	5.05
6	1.0500	7.00
7	1.0630	5.60
8	1.0300	5.40
9	1.0250	8.00
10	1.0100	5.00
11	1.0000	10.00
12	1.0156	13.50
13	1.0110	35.91
14	1.0000	17.85
15	1.0000	10.00
16	1.0000	40.00

Table A.2: Load Bus Data

<i>Bus number</i>	<i>Real load (p.u.)</i>	<i>Reactive load (p.u.)</i>
17	60.00	3.000
18	24.70	1.2300
19	0	0
20	6.80	1.0300
21	2.74	1.1500
22	0	0
23	2.48	0.8500
24	3.09	-0.9200
25	2.24	0.4700
26	1.39	0.1700

Table A.2: Load Bus Data (continued)

<i>Bus number</i>	<i>Real load (p.u.)</i>	<i>Reactive load (p.u.)</i>
27	2.81	0.7600
28	2.06	0.2800
29	2.84	0.2700
30	0	0
31	0	0
32	0	0
33	1.12	0
34	0	0
35	0	0
36	1.02	-0.1946
37	0	0
38	0	0
39	2.67	0.1260
40	0.6563	0.2353
41	10.00	2.5000
42	11.50	2.5000
43	0	0
44	2.6755	0.0484
45	2.08	0.2100
46	1.507	0.2850
47	2.0312	0.3259
48	2.412	0.0220
49	1.64	0.2900
50	1.00	-1.4700
51	3.37	-1.2200
52	1.58	0.3000
53	2.527	1.1856
54	0	0
55	3.22	0.0200
56	2.00	0.3760
57	0	0
58	0	0
59	2.34	0.8400
60	2.088	0.7080
61	1.04	1.2500
62	0	0
63	0	0
64	0.09	0.8800
65	0	0
66	0	0
67	3.20	1.53
68	3.29	0.3200
69	0	0

Table A.3: Line Data

<i>From bus</i>	<i>To bus</i>	<i>Resistance (pu)</i>	<i>Reactance (pu)</i>	<i>Line charging (pu)</i>	<i>Tap ratio</i>
54	1	0	0.0181	0	1.0250
58	2	0	0.0250	0	1.0700
62	3	0	0.0200	0	1.0700
19	4	0.0007	0.0142	0	1.0700
20	5	0.0009	0.0180	0	1.0090
22	6	0	0.0143	0	1.0250
23	7	0.0005	0.0272	0	0
25	8	0.0006	0.0232	0	1.0250
29	9	0.0008	0.0156	0	1.0250
31	10	0	0.0260	0	1.0400
32	11	0	0.0130	0	1.0400
36	12	0	0.0075	0	1.0400
17	13	0	0.0033	0	1.0400
41	14	0	0.0015	0	1.0000
42	15	0	0.0015	0	1.0000
18	16	0	0.0030	0	1.0000
36	17	0.0005	0.0045	0.3200	0
49	18	0.0076	0.1141	1.1600	0
68	19	0.0016	0.0195	0.3040	0
19	20	0.0007	0.0138	0	1.0600
68	21	0.0008	0.0135	0.2548	0
21	22	0.0008	0.0140	0.2565	0
22	23	0.0006	0.0096	0.1846	0
23	24	0.0022	0.0350	0.3610	0
68	24	0.0003	0.0059	0.0680	0
54	25	0.0070	0.0086	0.1460	0
25	26	0.0032	0.0323	0.5310	0
37	27	0.0013	0.0173	0.3216	0
26	27	0.0014	0.0147	0.2396	0
26	28	0.0043	0.0474	0.7802	0
26	29	0.0057	0.0625	1.0290	0
28	29	0.0014	0.0151	0.2490	0
53	30	0.0008	0.0074	0.4800	0
61	30	0.0019	0.0183	0.2900	0
61	30	0.0019	0.0183	0.2900	0
30	31	0.0013	0.0187	0.3330	0
53	31	0.0016	0.0163	0.2500	0
30	32	0.0024	0.0288	0.4880	0
32	33	0.0008	0.0099	0.1680	0
33	34	0.0011	0.0157	0.2020	0
35	34	0.0001	0.0074	0	0.9460
34	36	0.0033	0.0111	1.4500	0

Table A.3: Line Data (continued)

<i>From bus</i>	<i>To bus</i>	<i>Resistance (pu)</i>	<i>Reactance (pu)</i>	<i>Line charging (pu)</i>	<i>Tap ratio</i>
61	36	0.0022	0.0196	0.3400	0
61	36	0.0022	0.0196	0.3400	0
68	37	0.0007	0.0089	0.1342	0
31	38	0.0011	0.0147	0.2470	0
33	38	0.0036	0.0444	0.6930	0
41	40	0.0060	0.0840	3.1500	0
48	40	0.0020	0.0220	1.2800	0
42	41	0.0040	0.0600	2.2500	0
18	42	0.0040	0.0600	2.2500	0
17	43	0.0005	0.0276	0	0
39	44	0	0.0411	0	0
43	44	0.0001	0.0011	0	0
35	45	0.0007	0.0175	1.3900	0
39	45	0	0.0839	0	0
44	45	0.0025	0.0730	0	0
38	46	0.0022	0.0284	0.4300	0
53	47	0.0013	0.0188	1.3100	0
47	48	0.0025	0.0268	0.4000	0
47	48	0.0025	0.0268	0.4000	0
46	49	0.0018	0.0274	0.2700	0
45	51	0.0004	0.0105	0.7200	0
50	51	0.0009	0.0221	1.6200	0
37	52	0.0007	0.0082	0.1319	0
55	52	0.0011	0.0133	0.2138	0
53	54	0.0035	0.0411	0.6987	0
54	55	0.0013	0.0151	0.2572	0
55	56	0.0013	0.0213	0.2214	0
56	57	0.0008	0.0128	0.1342	0
57	58	0.0002	0.0026	0.0434	0
58	59	0.0006	0.0092	0.1130	0
57	60	0.0008	0.0112	0.1476	0
59	60	0.0004	0.0046	0.0780	0
60	61	0.0023	0.0363	0.3804	0
58	63	0.0007	0.0082	0.1389	0
62	63	0.0004	0.0043	0.0729	0
64	63	0.0016	0.0435	0	1.0600
62	65	0.0004	0.0043	0.0729	0
64	65	0.0016	0.0435	0	1.0600
56	66	0.0008	0.0129	0.1382	0
65	66	0.0009	0.0101	0.1723	0
66	67	0.0018	0.0217	0.3660	0
67	68	0.0009	0.0094	0.1710	0

Table A.3: Line Data (continued)

From bus	To bus	Resistance (pu)	Reactance (pu)	Line charging (pu)	Tap ratio
53	27	0.0320	0.3200	0.4100	1.0000
69	18	0.0006	0.0144	1.0300	0
50	69	0.0006	0.0144	1.0300	0

Table A.4: Synchronous Machine Dynamic Data

Machine	Bus	Base MVA	X_{ls} (pu)	R_s (pu)	X_d (pu)	X_d' (pu)	X_d'' (pu)	T_{do}' (sec)	T_{do}'' (sec)
1	1	100	0.0125	0.0	0.1	0.031	0.025	10.2	0.05
2	2	100	0.035	0.0	0.295	0.0697	0.05	6.56	0.05
3	3	100	0.0304	0.0	0.2495	0.0531	0.045	5.7	0.05
4	4	100	0.0295	0.0	0.262	0.0436	0.035	5.69	0.05
5	5	100	0.027	0.0	0.33	0.066	0.05	5.4	0.05
6	6	100	0.0224	0.0	0.254	0.05	0.04	7.3	0.05
7	7	100	0.0322	0.0	0.295	0.049	0.04	5.66	0.05
8	8	100	0.028	0.0	0.29	0.057	0.045	6.7	0.05
9	9	100	0.0298	0.0	0.2106	0.057	0.045	4.79	0.05
10	10	100	0.0199	0.0	0.169	0.0457	0.04	9.37	0.05
11	11	100	0.0103	0.0	0.128	0.018	0.012	4.1	0.05
12	12	100	0.022	0.0	0.101	0.031	0.025	7.4	0.05
13	13	200	0.0030	0.0	0.0296	0.0055	0.004	5.9	0.05
14	14	100	0.0017	0.0	0.018	0.00285	0.0023	4.1	0.05
15	15	100	0.0017	0.0	0.018	0.00285	0.0023	4.1	0.05
16	16	200	0.0041	0.0	0.0356	0.0071	0.0055	7.8	0.05

Table A.4: Synchronous Machine Dynamic Data (continued)

<i>Machine</i>	X_q (pu)	X_q' (pu)	X_q'' (pu)	T_{qo}' (sec)	T_{qo}'' (sec)	H (sec)	D
1	0.069	0.028	0.025	1.5	0.035	42.0	4.0
2	0.282	0.060	0.05	1.5	0.035	30.2	9.75
3	0.237	0.050	0.045	1.5	0.035	35.8	10
4	0.258	0.040	0.035	1.5	0.035	28.6	10
5	0.031	0.060	0.05	0.44	0.035	26.0	3
6	0.241	0.045	0.04	0.4	0.035	34.8	10
7	0.292	0.045	0.04	1.5	0.035	26.4	8
8	0.280	0.050	0.045	0.41	0.035	24.3	9
9	0.205	0.050	0.045	1.96	0.035	34.5	14
10	0.115	0.045	0.04	1.5	0.035	31.0	5.56
11	0.123	0.015	0.012	1.5	0.035	28.2	13.6
12	0.095	0.028	0.025	1.5	0.035	92.3	13.5
13	0.0286	0.005	0.004	1.5	0.035	248.0	33
14	0.0173	0.0025	0.0023	1.5	0.035	300.0	100
15	0.0173	0.0025	0.0023	1.5	0.035	300.0	100
16	0.0334	0.006	0.0055	1.5	0.035	225.0	50

Table A.5: IEEE DC1A Excitation System Data

<i>Machine</i> <i>no.</i>	T_r (sec)	K_A	T_A (sec)	V_{rma} x (pu)	V_{rmin} (pu)	K_E	T_E (sec)	A_{ex}	B_{ex}	K_f	T_f (sec)
1	0.01	40	0.02	0.15	-0.15	1	0.785	0.07	0.91	0.058	0.62
2	0.01	40	0.02	0.15	-0.15	1	0.785	0.07	0.91	0.058	0.62
3	0.01	40	0.02	0.15	-0.15	1	0.785	0.07	0.91	0.058	0.62
4	0.01	40	0.02	0.15	-0.15	1	0.785	0.07	0.91	0.058	0.62
5	0.01	40	0.02	0.15	-0.15	1	0.785	0.07	0.91	0.058	0.62
6	0.01	40	0.02	0.15	-0.15	1	0.785	0.07	0.91	0.058	0.62
7	0.01	40	0.02	0.15	-0.15	1	0.785	0.07	0.91	0.058	0.62
8	0.01	40	0.02	0.15	-0.15	1	0.785	0.07	0.91	0.058	0.62

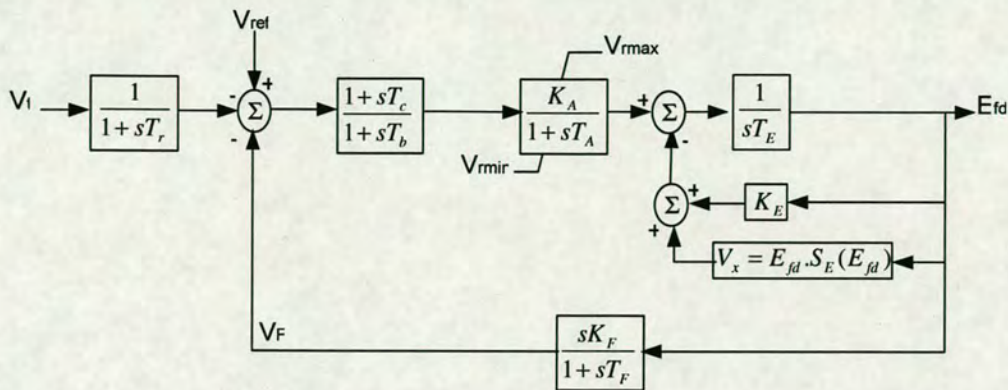


Figure A.1 Block Diagram of DC Exciter Model

Table A.6: Static Excitation System Data and PSS Data

Machine no.	T_r (sec)	K_A	T_A (sec)	V_{imax} (pu)	V_{imin} (pu)	T_C (sec)	T_B (sec)	V_{rmax} (pu)	V_{rmin} (pu)
9	0.01	200	0.01	0.15	-0.15	1.4	20.4	5	-5

Table A.6: Static Excitation System Data and PSS Data (continued)

Machine no.	K_{pss}	T_1 (sec)	T_2 (sec)	T_3 (sec)	T_4 (sec)
9	$\frac{12}{377}$	0.1	0.2	0.1	0.2

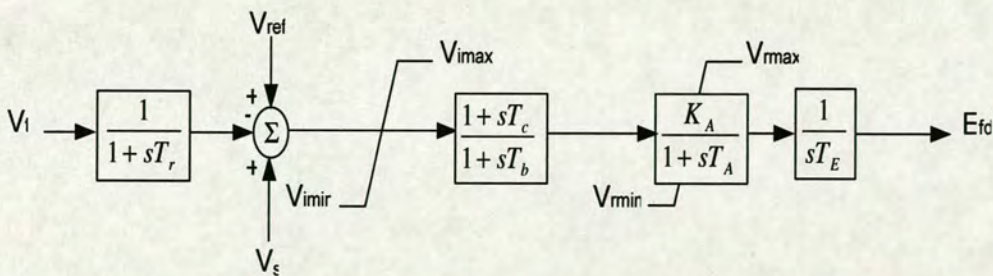


Figure A.2 Block Diagram of Static Exciter Model

Table A.7 Static Excitation System Data

Machine no.	K_A	T_A (sec)	V_{imax} (pu)	V_{imin} (pu)	T_C (sec)	T_B (sec)	V_{rmax} (pu)	V_{rmin} (pu)
14	200	0.01	0.15	-0.15	1.4	20.4	5	-5
15	200	0.01	0.15	-0.15	1.4	20.4	5	-5
16	200	0.01	0.15	-0.15	1.4	20.4	5	-5

A.2 6-Machine 3-Area Test System Data

Table A.8: Machine Bus Data

<i>Bus number</i>	<i>Voltage (p.u.)</i>	<i>Power generation (p.u.)</i>
1	1.03	0.256
2	1.01	0.666
3	1.03	0.687
4	1.01	0.666
5	1.0	0.899
6	1.0	0.899

Table A.9: Load Bus Data

<i>Bus number</i>	<i>Real load (p.u.)</i>	<i>Reactive load (p.u.)</i>
7	14.00	1.00
9	17.67	1.00

Table A.10: Line Data

<i>From bus</i>	<i>To bus</i>	<i>Resistance (pu)</i>	<i>Reactance (pu)</i>	<i>Line charging (pu)</i>	<i>Tap ratio</i>
1	14	0	0.0166	0	1.0000
2	16	0	0.0166	0	1.0000
3	11	0	0.0166	0	1.0000
4	10	0	0.0166	0	1.0000
5	15	0	0.027	0	1.0000
6	13	0	0.027	0	1.0000
7	8	0.011	0.11	0.19250	1.0000
7	8	0.011	0.11	0.19250	1.0000
8	9	0.011	0.11	0.19250	1.0000
8	9	0.011	0.11	0.19250	1.0000
9	10	0.001	0.01	0.0175	1.0000
10	11	0.0025	0.025	0.04375	1.0000
12	7	0.022	0.22	0.04812	1.0000
12	7	0.022	0.22	0.04812	1.0000
12	9	0.022	0.22	0.04812	1.0000
12	9	0.022	0.22	0.04812	1.0000

Table A.11: Line Data (continued)

From bus	To bus	Resistance (pu)	Reactance (pu)	Line charging (pu)	Tap ratio
12	13	0.001	0.01	0.01750	1.0000
13	15	0.0025	0.025	0.04374	1.0000
14	16	0.0025	0.025	0.04374	1.0000
16	7	0.001	0.01	0.01750	1.0000

Table A.12: Synchronous Machine Dynamic Data

Machine	Bus	Base MVA	X_{ls} (pu)	R_s (pu)	X_d (pu)	X_d' (pu)	X_d'' (pu)	T_{do}' (sec)	T_{do}'' (sec)
1	1	900	0.2	0.0025	1.80	0.3	0.25	8.0	0.03
2	2	900	0.2	0.0025	1.80	0.3	0.25	8.0	0.03
3	3	900	0.2	0.0025	1.80	0.3	0.25	8.0	0.03
4	4	900	0.2	0.0025	1.80	0.3	0.25	8.0	0.03
5	5	555	0.15	0.0030	1.81	0.3	0.25	8.0	0.03
6	6	555	0.15	0.0030	1.81	0.3	0.25	8.0	0.03

Table A.13: Synchronous Machine Dynamic Data (continued)

Machine	X_q (pu)	X_q' (pu)	X_q'' (pu)	T_{qo}' (sec)	T_{qo}'' (sec)	H (sec)	D
1	1.7	0.55	0.25	0.4	0.05	6.50	0
2	1.7	0.55	0.25	0.4	0.05	6.50	0
3	1.7	0.55	0.25	0.4	0.05	6.175	0
4	1.7	0.55	0.25	0.4	0.05	6.175	0
5	1.76	0.65	0.25	1.0	0.03	6.45	0
6	1.76	0.65	0.25	1.0	0.03	6.45	0

Table A.14: Static Excitation System Data and PSS Data

<i>Machine no.</i>	<i>Tr (sec)</i>	<i>K_A</i>	<i>T_A (sec)</i>	<i>V_{imax} (pu)</i>	<i>V_{imin} (pu)</i>	<i>T_C (sec)</i>	<i>T_B (sec)</i>	<i>V_{rmax} (pu)</i>	<i>V_{rmin} (pu)</i>
1	0.01	250	0.01	0.15	-0.15	1.4	20.4	5.64	-4.53
2	0.01	250	0.01	0.15	-0.15	1.4	20.4	5.64	-4.53
3	0.01	250	0.01	0.15	-0.15	1.4	20.4	5.64	-4.53
4	0.01	250	0.01	0.15	-0.15	1.4	20.4	5.64	-4.53
5	0.01	250	0.01	0.15	-0.15	1.4	20.4	5.64	-4.53
6	0.01	250	0.01	0.15	-0.15	1.4	20.4	5.64	-4.53

Table A.15: Static Excitation System Data and PSS Data (continued)

<i>Machine no.</i>	<i>K_{pss}</i>	<i>T₁ (sec)</i>	<i>T₂ (sec)</i>	<i>T₃ (sec)</i>	<i>T₄ (sec)</i>
1	0.65	1.45	0.04	0.986	0.014
2	0.65	1.45	0.04	0.986	0.014
3	0.65	1.45	0.04	0.986	0.014
4	0.65	1.45	0.04	0.986	0.014
5	0.65	1.25	0.03	0.756	0.010
6	0.65	1.25	0.03	0.756	0.010

A.3 4-Machine 2-Area Test System Data

Table A.16: Machine Bus Data

<i>Bus number</i>	<i>Voltage (p.u.)</i>	<i>Power generation (p.u.)</i>
1	1.03	0.6602
2	1.01	0.7778
3	1.03	0.7989
4	1.01	0.7778

Table A.17: Load Bus Data

<i>Bus number</i>	<i>Real load (p.u.)</i>	<i>Reactive load (p.u.)</i>
7	9.67	1.00
9	17.67	1.00

Table A.18: Line Data

<i>From bus</i>	<i>To bus</i>	<i>Resistance (pu)</i>	<i>Reactance (pu)</i>	<i>Line charging (pu)</i>	<i>Tap ratio</i>
1	5	0	0.0166	0	1.0000
2	6	0	0.0166	0	1.0000
3	11	0	0.0166	0	1.0000
4	10	0	0.0166	0	1.0000
5	6	0.0025	0.025	0.04375	1.0000
6	7	0.001	0.01	0.01750	1.0000
7	8	0.011	0.11	0.19250	1.0000
7	8	0.011	0.11	0.19250	1.0000
8	9	0.011	0.11	0.19250	1.0000
8	9	0.011	0.11	0.19250	1.0000
9	10	0.001	0.01	0.01750	1.0000
10	11	0.0025	0.025	0.04375	1.0000

Table A.19: Synchronous Machine Dynamic Data

Machine	Bus	Base MVA	X_{ls} (pu)	R_s (pu)	X_d (pu)	X_d' (pu)	X_d'' (pu)	T_{do}' (sec)	T_{do}'' (sec)
1	1	900	0.2	0.0025	1.80	0.3	0.25	8.0	0.03
2	2	900	0.2	0.0025	1.80	0.3	0.25	8.0	0.03
3	3	900	0.2	0.0025	1.80	0.3	0.25	8.0	0.03
4	4	900	0.2	0.0025	1.80	0.3	0.25	8.0	0.03

Table A.20: Synchronous Machine Dynamic Data (continued)

Machine	X_q (pu)	X_q' (pu)	X_q'' (pu)	T_{qo}' (sec)	T_{qo}'' (sec)	H (sec)	D
1	1.7	0.55	0.25	0.4	0.05	6.50	0
2	1.7	0.55	0.25	0.4	0.05	6.50	0
3	1.7	0.55	0.25	0.4	0.05	6.175	0
4	1.7	0.55	0.25	0.4	0.05	6.175	0

Table A.21: Static Excitation System Data and PSS Data

Machine no.	T_r (sec)	K_A	T_A (sec)	V_{imax} (pu)	V_{imin} (pu)	T_C (sec)	T_B (sec)	V_{rmax} (pu)	V_{rmin} (pu)
1	0.01	250	0.01	0.15	-0.15	1.4	20.4	5.64	-4.53
2	0.01	250	0.01	0.15	-0.15	1.4	20.4	5.64	-4.53
3	0.01	250	0.01	0.15	-0.15	1.4	20.4	5.64	-4.53
4	0.01	250	0.01	0.15	-0.15	1.4	20.4	5.64	-4.53

Table A.22: Static Excitation System Data and PSS Data (continued)

Machine no.	K_{pss}	T_1 (sec)	T_2 (sec)	T_3 (sec)	T_4 (sec)
1	0.25	1.45	0.04	0.986	0.014
2	0.25	1.45	0.04	0.986	0.014
3	0.25	1.45	0.04	0.986	0.014
4	0.25	1.45	0.04	0.986	0.014

Bus 7: $Q_c = 200$ MVar

Bus 9: $Q_c = 350$ MVar

A.4 Parameter Calculations

The following equations are used to calculate machines' reactances and resistances that are used in equations in chapter 5:

$$X_{ad} = X_d - X_l \quad \text{A.1}$$

$$X_{aq} = X_q - X_l \quad \text{A.2}$$

$$T_d'' = T_{do}'' \left(\frac{X_d''}{X_d'} \right) \quad \text{A.3}$$

$$T_d' = T_{do}' \left(\frac{X_d'}{X_d} \right) \quad \text{A.4}$$

$$T_q'' = T_{qo}'' \left(\frac{X_q''}{X_q'} \right) \quad \text{A.5}$$

$$T_q' = T_{qo}' \left(\frac{X_q'}{X_q} \right) \quad \text{A.6}$$

$$X_{ld} = X_{ad} \left(\frac{(X_d' - X_l)(X_d'' - X_l)}{(X_d' - X_d'')} \right) \quad \text{A.7}$$

$$X_{lq} = X_{aq} \left(\frac{(X_q'' - X_l)}{(X_q - X_q'')} \right) \quad \text{A.8}$$

$$X_{fd} = \frac{X_{ad}(X_l - X_d')}{(X_d' - X_{ad} - X_l)} \quad \text{A.9}$$

$$R_{ld} = \frac{1}{\omega_{gn} T_d''} \frac{X_d''}{X_d'} \frac{(X_d' - X_l)^2}{(X_d' - X_d'')} \quad \text{A.10}$$

$$R_{lq} = \frac{1}{\omega_{gn} T_q''} \frac{X_q''}{X_q} \frac{(X_{aq})^2}{(X_q - X_q'')} \quad \text{A.11}$$

$$R_{fd} = \frac{1}{\omega_{gn} T_d'} \frac{X_d'}{X_d} \frac{(X_{ad})^2}{(X_d - X_d')} \quad \text{A.12}$$

$$X_{fld} = X_{ad} \quad \text{A.13}$$

$$X_{11d} = X_{ld} + X_{ad} \quad \text{A.14}$$

$$X_{11q} = X_{lq} + X_{aq} \quad \text{A.15}$$

$$X_{ffd} = X_{fd} + X_{ad} \quad \text{A.16}$$

where,

X_d : d-axis synchronous reactance,

X_q : q-axis synchronous reactance,

X_l : stator leakage reactance,

X_{ad} : d-axis mutual reactance,

X_{aq} : q-axis mutual reactance,

X'_d : d-axis transient synchronous reactance,

X''_d : d-axis subtransient synchronous reactance,

X'_q : q-axis transient synchronous reactance,

X''_q : q-axis subtransient synchronous reactance,

T'_{do} : d-axis transient open-circuit time constant,

T'_{qo} : q-axis transient open-circuit time constant,

T''_{do} : d-axis subtransient open-circuit time constant,

T''_{qo} : q-axis subtransient open-circuit time constant,

T'_d : d-axis transient short-circuit time constant,

T'_q : q-axis transient short-circuit time constant,

T''_d : d-axis subtransient short-circuit time constant,

T''_q : q-axis subtransient short-circuit time constant,

R_{ld} : d-axis rotor circuit resistance,

R_{lq} : q-axis rotor circuit resistance,

R_{fd} : d-axis field circuit resistance,

X_{ld} : d-axis amortisseur circuit reactance,

X_{lq} : q-axis amortisseur circuit reactance,

X_{fd} : field reactance,

X_{lld} : d-axis self-reactance,

X_{llq} : q-axis self-reactance, and

ω_{gn} : rated-rotor angular velocity.

Appendix B

B.1 Type 1 SPSS and Type 3 SPSS Control Rules

THIS section of Appendix B presents the control rules for Type 1 and Typ3 fuzzy-based SPSS. In All SPSS types, the same decision table (i.e. control rules) presented in chapter 6 and shown below for convenience is used; merely, the evaluation of control rules is different since the numbers of input variables of Type 1 and 3 are less than the number of input variables for Type 3.

$\Delta\omega \backslash \frac{d\Delta\omega}{dt}$	NB	NM	Z	PM	PB
NB	NB	NB	NM	NM	Z
NM	NB	NM	NM	Z	PM
Z	NM	NM	Z	PM	PM
PM	NM	Z	PM	PM	PB
PB	Z	PM	PM	PB	PB

Table B.1 Decision Table for SPSS Output

Rule 1: If $\Delta\omega$ is NB AND $\frac{d\Delta\omega}{dt}$ is NB THEN V_{spss} is NB.

Rule 2: If $\Delta\omega$ is NB AND $\frac{d\Delta\omega}{dt}$ is NM THEN V_{spss} is NB.

Rule 3: If $\Delta\omega$ is NB AND $\frac{d\Delta\omega}{dt}$ is Z THEN V_{spss} is NM.

Rule 4: If $\Delta\omega$ is NB AND $\frac{d\Delta\omega}{dt}$ is PM THEN V_{spss} is NM.

Rule 5: If $\Delta\omega$ is NB AND $\frac{d\Delta\omega}{dt}$ is PB THEN V_{spss} is Z.

Rule 6: If $\Delta\omega$ is NM AND $\frac{d\Delta\omega}{dt}$ is NB THEN V_{spss} is NB.

Rule 7: If $\Delta\omega$ is NM AND $\frac{d\Delta\omega}{dt}$ is NM THEN V_{spss} is NM

Rule 8: If $\Delta\omega$ is NM AND $\frac{d\Delta\omega}{dt}$ is Z THEN V_{spss} is NM.

Rule 9: If $\Delta\omega$ is NM AND $\frac{d\Delta\omega}{dt}$ is PM THEN V_{spss} is Z.

Rule 10: If $\Delta\omega$ is NM AND $\frac{d\Delta\omega}{dt}$ is PB THEN V_{spss} is PM.

Rule 11: If $\Delta\omega$ is Z AND $\frac{d\Delta\omega}{dt}$ is NB THEN V_{spss} is NM.

Rule 12: If $\Delta\omega$ is Z AND $\frac{d\Delta\omega}{dt}$ is NM THEN V_{spss} is NM

Rule 13: If $\Delta\omega$ is Z AND $\frac{d\Delta\omega}{dt}$ is Z THEN V_{spss} is Z.

Rule 14: If $\Delta\omega$ is Z AND $\frac{d\Delta\omega}{dt}$ is PM THEN V_{spss} is PM.

Rule 15: If $\Delta\omega$ is Z AND $\frac{d\Delta\omega}{dt}$ is PB THEN V_{spss} is PM.

Rule 16: If $\Delta\omega$ is PM AND $\frac{d\Delta\omega}{dt}$ is NB THEN V_{spss} is NM.

Rule 17: If $\Delta\omega$ is PM AND $\frac{d\Delta\omega}{dt}$ is NM THEN V_{spss} is Z.

Rule 18: If $\Delta\omega$ is PM AND $\frac{d\Delta\omega}{dt}$ is Z THEN V_{spss} is PM.

Rule 19: If $\Delta\omega$ is PM AND $\frac{d\Delta\omega}{dt}$ is PM THEN V_{spss} is PM.

Rule 20: If $\Delta\omega$ is PM AND $\frac{d\Delta\omega}{dt}$ is PB THEN V_{spss} is PB.

Rule 21: If $\Delta\omega$ is PB AND $\frac{d\Delta\omega}{dt}$ is NB THEN V_{spss} is Z

Rule 22: If $\Delta\omega$ is PB AND $\frac{d\Delta\omega}{dt}$ is NM THEN V_{spss} is PM.

Rule 23: If $\Delta\omega$ is PB AND $\frac{d\Delta\omega}{dt}$ is Z THEN V_{spss} is PM.

Rule 24: If $\Delta\omega$ is PB AND $\frac{d\Delta\omega}{dt}$ is PM THEN V_{spss} is PB.

Rule 25: If $\Delta\omega$ is PB AND $\frac{d\Delta\omega}{dt}$ is PB THEN V_{spss} is PB.

B.2 Type 2 SPSS Control Rules

If we assume Type 2 SPSS is applied to 6-machine 3-area system, and then there will be six input variables to each fuzzy controller within the SPSS in order to generate stabilizing signals, Fig. B.1.

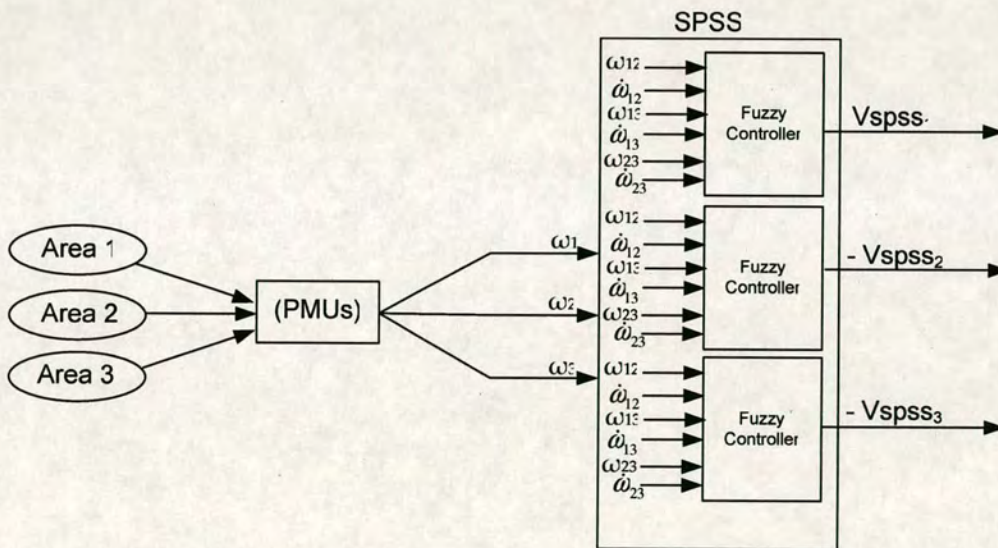


Figure B.1 Structure of Type 2 SPSS for 6-machin 3-area Test Model

The control rules that will generate for example the stabilizing signal for area 1 are as follows:

Rule 1: If ($\Delta\omega_{12}$ is NB AND $\frac{d\Delta\omega_{12}}{dt}$ is NB) OR ($\Delta\omega_{13}$ is NB AND $\frac{d\Delta\omega_{13}}{dt}$ is NB)
THEN V_{spss} is NB.

Rule 2: If ($\Delta\omega_{12}$ is NB AND $\frac{d\Delta\omega_{12}}{dt}$ is NM) OR ($\Delta\omega_{13}$ is NB AND $\frac{d\Delta\omega_{13}}{dt}$ is NM)

THEN Vspss is NB.

Rule 3: If ($\Delta\omega_{12}$ is NB AND $\frac{d\Delta\omega_{12}}{dt}$ is Z) OR ($\Delta\omega_{13}$ is NB AND $\frac{d\Delta\omega_{13}}{dt}$ is Z)

THEN Vspss is NM.

Rule 4: If ($\Delta\omega_{12}$ is NB AND $\frac{d\Delta\omega_{12}}{dt}$ is PM) OR ($\Delta\omega_{13}$ is NB AND $\frac{d\Delta\omega_{13}}{dt}$ is PM)

THEN Vspss is NM.

Rule 5: If ($\Delta\omega_{12}$ is NB AND $\frac{d\Delta\omega_{12}}{dt}$ is PB) OR ($\Delta\omega_{13}$ is NB AND $\frac{d\Delta\omega_{13}}{dt}$ is PB)

THEN Vspss is Z.

Rule 6: If ($\Delta\omega_{12}$ is NM AND $\frac{d\Delta\omega_{12}}{dt}$ is NB) OR ($\Delta\omega_{13}$ is NM AND $\frac{d\Delta\omega_{13}}{dt}$ is NB)

THEN Vspss is NB.

Rule 7: If ($\Delta\omega_{12}$ is NM AND $\frac{d\Delta\omega_{12}}{dt}$ is NM) OR ($\Delta\omega_{13}$ is NM AND $\frac{d\Delta\omega_{13}}{dt}$ is

NM) THEN Vspss is NM.

Rule 8: If ($\Delta\omega_{12}$ is NM AND $\frac{d\Delta\omega_{12}}{dt}$ is Z) OR ($\Delta\omega_{13}$ is NM AND $\frac{d\Delta\omega_{13}}{dt}$ is Z)

THEN Vspss is NM.

Rule 9: If ($\Delta\omega_{12}$ is NM AND $\frac{d\Delta\omega_{12}}{dt}$ is PM) OR ($\Delta\omega_{13}$ is NM AND $\frac{d\Delta\omega_{13}}{dt}$ is

PM) THEN Vspss is Z.

Rule 10: If ($\Delta\omega_{12}$ is NM AND $\frac{d\Delta\omega_{12}}{dt}$ is PB) OR ($\Delta\omega_{13}$ is NM AND $\frac{d\Delta\omega_{13}}{dt}$ is PB)

THEN Vspss is PM.

Rule 11: If ($\Delta\omega_{12}$ is Z AND $\frac{d\Delta\omega_{12}}{dt}$ is NB) OR ($\Delta\omega_{13}$ is Z AND $\frac{d\Delta\omega_{13}}{dt}$ is NB)

THEN Vspss is NM.

Rule 12: If $(\Delta\omega_{12} \text{ is Z AND } \frac{d\Delta\omega_{12}}{dt} \text{ is NM}) \text{ OR } (\Delta\omega_{13} \text{ is Z AND } \frac{d\Delta\omega_{13}}{dt} \text{ is NM})$

THEN Vspss is NM.

Rule 13: If $(\Delta\omega_{12} \text{ is Z AND } \frac{d\Delta\omega_{12}}{dt} \text{ is Z}) \text{ OR } (\Delta\omega_{13} \text{ is Z AND } \frac{d\Delta\omega_{13}}{dt} \text{ is Z})$ THEN

Vspss is Z.

Rule 14: If $(\Delta\omega_{12} \text{ is Z AND } \frac{d\Delta\omega_{12}}{dt} \text{ is PM}) \text{ OR } (\Delta\omega_{13} \text{ is Z AND } \frac{d\Delta\omega_{13}}{dt} \text{ is PM})$

THEN Vspss is PM.

Rule 15: If $(\Delta\omega_{12} \text{ is Z AND } \frac{d\Delta\omega_{12}}{dt} \text{ is PB}) \text{ OR } (\Delta\omega_{13} \text{ is Z AND } \frac{d\Delta\omega_{13}}{dt} \text{ is PB})$

THEN Vspss is PM.

Rule 16: If $(\Delta\omega_{12} \text{ is PM AND } \frac{d\Delta\omega_{12}}{dt} \text{ is NB}) \text{ OR } (\Delta\omega_{13} \text{ is PM AND } \frac{d\Delta\omega_{13}}{dt} \text{ is NB})$

THEN Vspss is NM.

Rule 17: If $(\Delta\omega_{12} \text{ is PM AND } \frac{d\Delta\omega_{12}}{dt} \text{ is NM}) \text{ OR } (\Delta\omega_{13} \text{ is PM AND } \frac{d\Delta\omega_{13}}{dt} \text{ is NM})$

THEN Vspss is Z.

Rule 18: If $(\Delta\omega_{12} \text{ is PM AND } \frac{d\Delta\omega_{12}}{dt} \text{ is Z}) \text{ OR } (\Delta\omega_{13} \text{ is PM AND } \frac{d\Delta\omega_{13}}{dt} \text{ is Z})$

THEN Vspss is PM.

Rule 19: If $(\Delta\omega_{12} \text{ is PM AND } \frac{d\Delta\omega_{12}}{dt} \text{ is PM}) \text{ OR } (\Delta\omega_{13} \text{ is PM AND } \frac{d\Delta\omega_{13}}{dt} \text{ is PM})$

THEN Vspss is PM.

Rule 20: If $(\Delta\omega_{12} \text{ is PM AND } \frac{d\Delta\omega_{12}}{dt} \text{ is PB}) \text{ OR } (\Delta\omega_{13} \text{ is PM AND } \frac{d\Delta\omega_{13}}{dt} \text{ is PB})$

THEN Vspss is PB.

Rule 21: If $(\Delta\omega_{12} \text{ is PB AND } \frac{d\Delta\omega_{12}}{dt} \text{ is NB}) \text{ OR } (\Delta\omega_{13} \text{ is PB AND } \frac{d\Delta\omega_{13}}{dt} \text{ is NB})$

THEN Vspss is Z.

Rule 22: If ($\Delta\omega_{12}$ is PB AND $\frac{d\Delta\omega_{12}}{dt}$ is NM) OR ($\Delta\omega_{13}$ is PB AND $\frac{d\Delta\omega_{13}}{dt}$ is NM)

THEN Vspss is PM.

Rule 23: If ($\Delta\omega_{12}$ is PB AND $\frac{d\Delta\omega_{12}}{dt}$ is Z) OR ($\Delta\omega_{13}$ is PB AND $\frac{d\Delta\omega_{13}}{dt}$ is Z)

THEN Vspss is PM.

Rule 24: If ($\Delta\omega_{12}$ is PB AND $\frac{d\Delta\omega_{12}}{dt}$ is PM) OR ($\Delta\omega_{13}$ is PB AND $\frac{d\Delta\omega_{13}}{dt}$ is PM)

THEN Vspss is PB.

Rule 25: If ($\Delta\omega_{12}$ is PB AND $\frac{d\Delta\omega_{12}}{dt}$ is PB) OR ($\Delta\omega_{13}$ is PB AND $\frac{d\Delta\omega_{13}}{dt}$ is PB)

THEN Vspss is PB.

For the other fuzzy controllers, the same control rules are applied with the exception of changing the subscripts of input variables. For example, the input variables that will be evaluated to generate Vspss₂ will be $\Delta\omega_{12}$, $d\Delta\omega_{12}/dt$, $\Delta\omega_{23}$ and finally $d\Delta\omega_{23}/dt$. Clearly, only input variables showing the involvement of *i*th area in the calculation of the speed differences are evaluated simultaneously to determine the *i*th SPSS output, Vspss_{*n*}.

Appendix C

C.1 16-Machine 5-Area Test Model

C.1.1 Type 1 SPSS

Case 1: extreme disturbance is applied to voltage reference of G16 and load reference of G1 at the same time while generating power of G2 and G12 is reduced to %50 of its full-rated power initially. The disturbance is simulated with 20 ms time delay and assumption of no loss of SPSS signals.

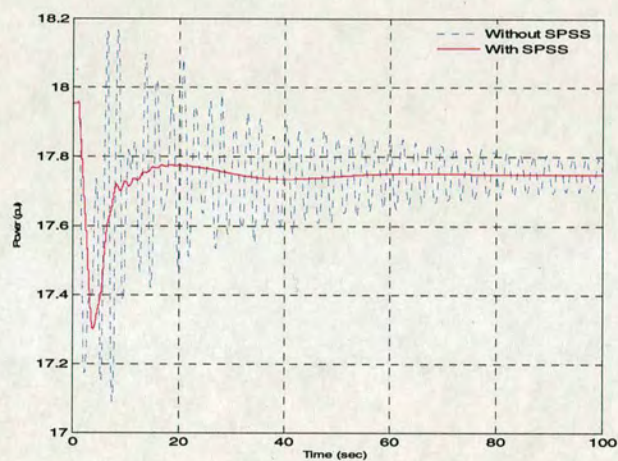


Figure C.1 Dynamic response of G13 with and without SPSS

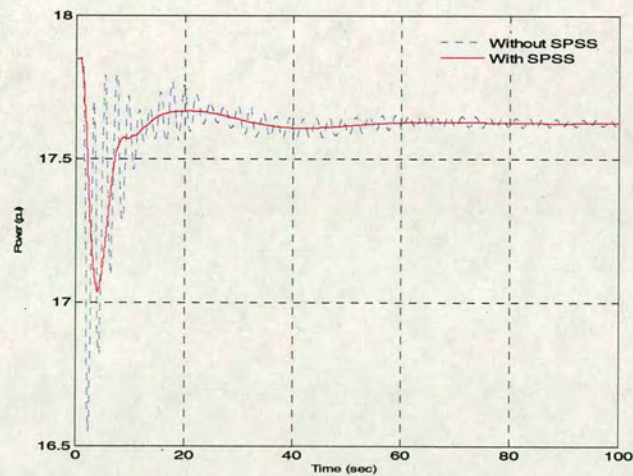


Figure C.2 Dynamic response of G14 with and without SPSS

Case 2: Unit step disturbance is applied to voltage reference of G13 at $t = 1$ s and then a short circuit is applied at bus 60 from fault duration of 100 ms (i.e. $t = 3$ to $t = 3.1$ sec with assumption there is a loss of SPSS signal to at G4 and G5.

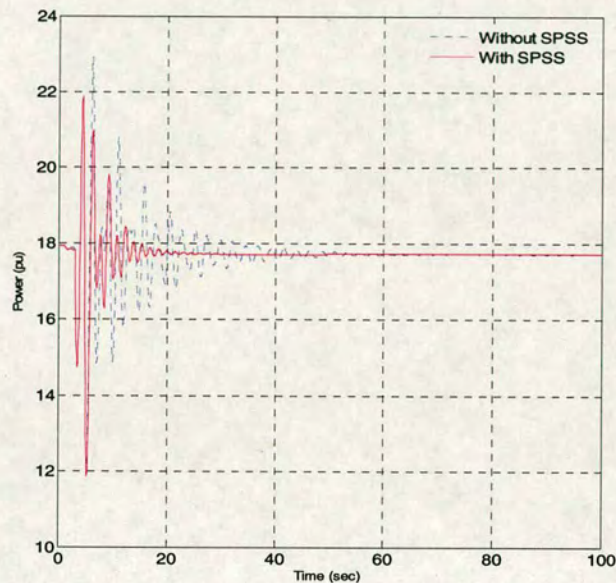


Figure C.4 Dynamic response of G13 with and without SPSS

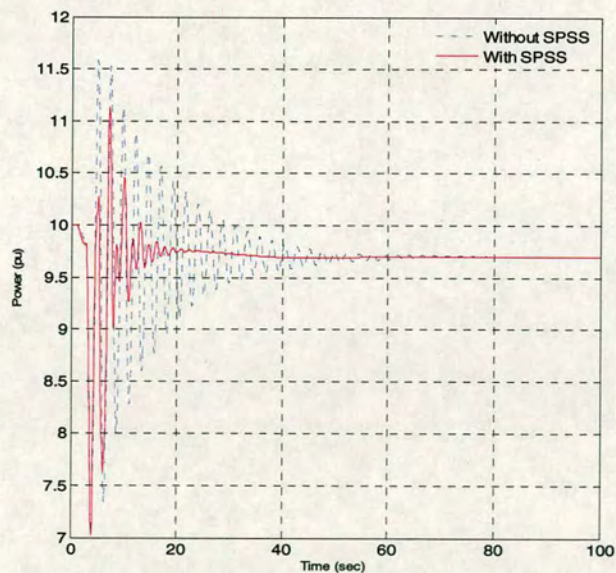


Figure C.4 Dynamic response of G15 with and without SPSS

Case 3: Disconnection of Generator

When a synchronous generator is disconnected from the power network, the rest of the generators must compensate for the lost power generation by the disconnected generator. So when there is a drop of MW generation, the load demand becomes greater than the generated power (i.e. $P_L > P_g$) with the assumption that the loads connected to the network remain unchanged, so the frequency will drop which corresponds to drop in speed deviations as clearly visible from the following equation:

$$2H_j(dw/dt) = P_g - P_l$$

Since action of turbine is normally slow, it will gradually increase the mechanical power so that the electrical power produced by the synchronous generators meet the load demands. At the same time, the speed deviation will also be gradually decreased until the new operating point is reached. Hence, the output power of each synchronous generator for the new system structure will be higher than the generated power prior to the generator disconnection.

In the case considered for the 16-machine 5-area system, the disconnection of generator 10 leads to the power outputs less than the values prior to the generator disconnection. This is because prior to the disconnection, the existence of generator 10 keeps the bus voltages at high level at bus 10 and buses electrically close to Bus 10, but when it is disconnected, the bus voltages drop few percent. Since the power is proportional to the square of the voltage, voltage drop causes the load power drop higher than the power of disconnected generator which means that the frequency is going up. And the output power of each generator drops as well. The following table shows the voltages and power consumed at load buses before and after the disconnection of G10:

Load No.	Voltage (p.u)		Power (p.u)	
	Before	After	Before	After
17	0.98942	0.97502	58.74	57.04
18	1.0013	1.0012	29.08	29.07
20	0.99134	0.90684	6.683	5.592
21	1.0341	0.94846	2.93	2.465
23	1.0455	0.95428	2.711	2.258
24	1.0419	0.95946	3.354	2.845
25	1.0595	1.0136	2.515	2.301
26	1.0563	1.0132	1.551	1.427
27	1.0444	0.98949	3.065	2.751
28	1.0513	1.0295	2.277	2.183
29	1.0504	1.0354	3.133	3.045
33	1.0458	1.0238	1.225	1.174
36	1.0154	0.99696	1.52	1.014
39	1.0161	1.0042	2.756	2.692
40	1.0842	1.0668	0.7715	0.7469
41	1.0002	1.0001	10	10
42	0.99912	0.99908	11.48	11.48
44	1.0072	0.99437	2.714	2.645
45	1.0596	1.0486	2.336	2.287
46	1.044	1.0227	1.643	1.576
47	1.0774	1.0497	2.358	2.238
48	1.0857	1.0619	2.843	2.72
49	1.0346	1.0174	1.755	1.698
50	1.0638	1.0617	1.132	1.127
51	1.0734	1.0657	3.883	3.827
52	1.0389	0.97239	1.705	1.494
53	1.0548	1.0219	2.811	2.639
55	1.0407	0.9797	3.488	3.091
56	1.0236	0.95764	2.096	1.834
59	1.0131	0.94939	2.402	2.109
60	1.0134	0.95086	2.144	1.888
61	1.0253	0.9957	1.093	1.031
64	1.063	0.99159	0.1017	0.08849
67	1.0225	0.9463	3.346	2.866
68	1.0367	0.9567	3.536	3.011
Total	36.30398	34.96163	185.1782	176.2534
% Voltage Change	1.883587			
% Power Change	2.469294			

Table C.1 Voltages before and after G10 removal from the system

In case 3, G10 is disconnected at $t = 3$ sec with assumption of no loss of SPSS signals.

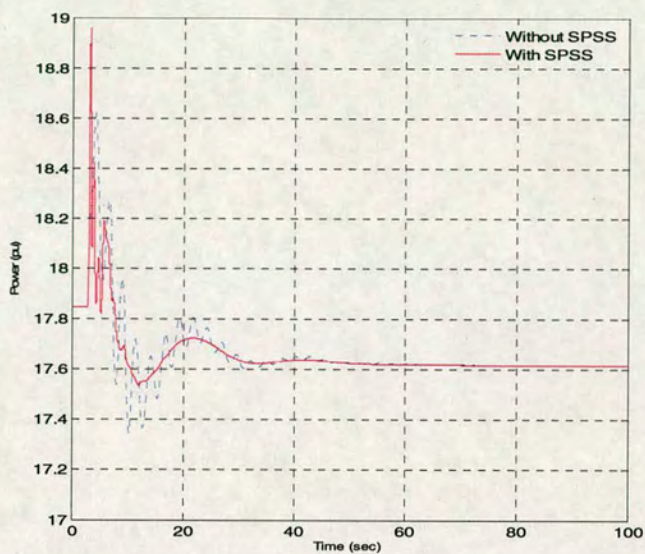


Figure C.5 Dynamic response of G14 with and without SPSS

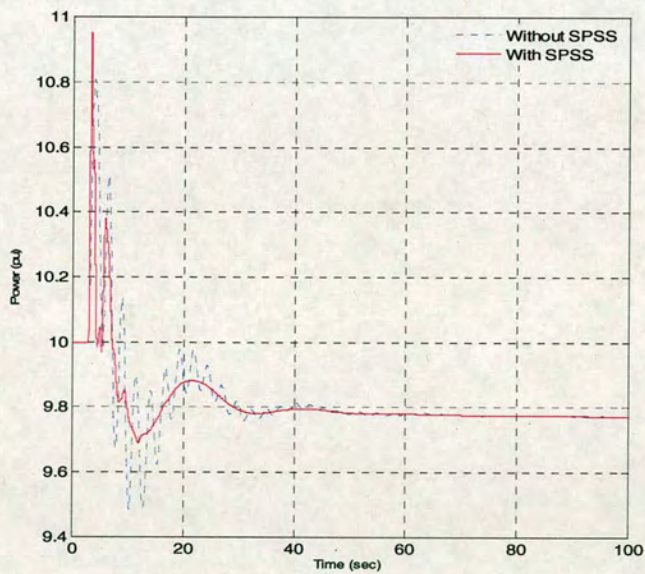


Figure C.6 Dynamic response of G15 with and without SPSS

C.1.2 Type 2 SPSS

Case 1: G10 is disconnected at $t = 3$ sec and the loads are unchanged. There is a loss of SPSS signals to some generators in area 1.

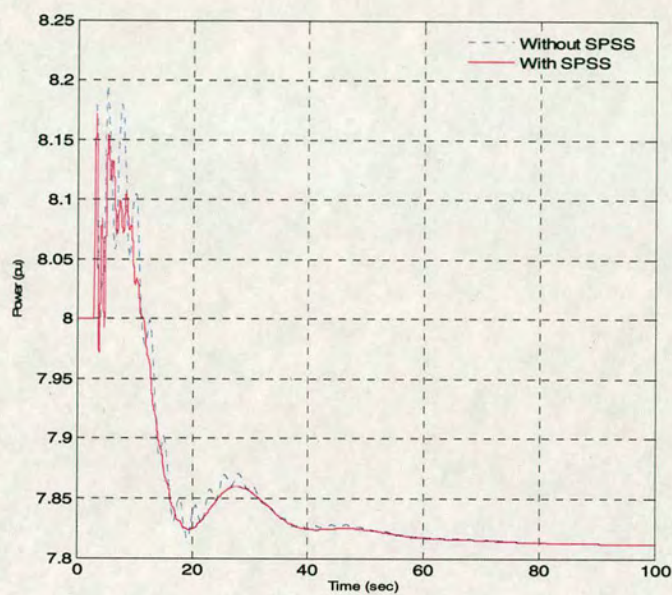


Figure C.6 Dynamic response of G9 with and without SPSS

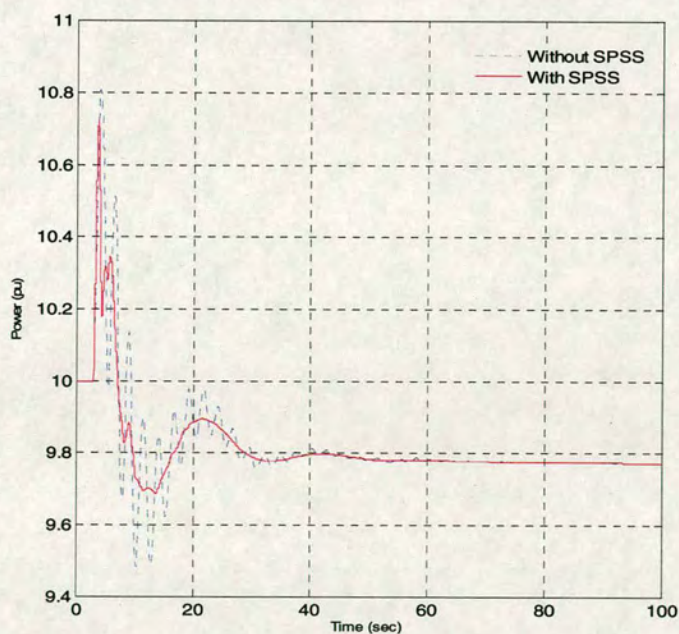


Figure C.7 Dynamic Response of G15 with and without SPSS

Case 2: the system is disturbed with a 0.05% unit step changed applied to voltage reference of G13 with a time delay of 20 ms.

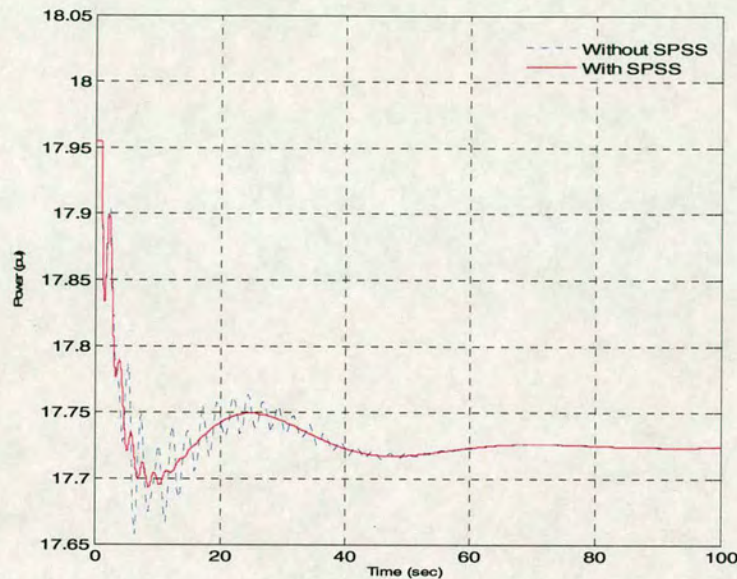


Figure C.8 Dynamic response of G13 with and without SPSS

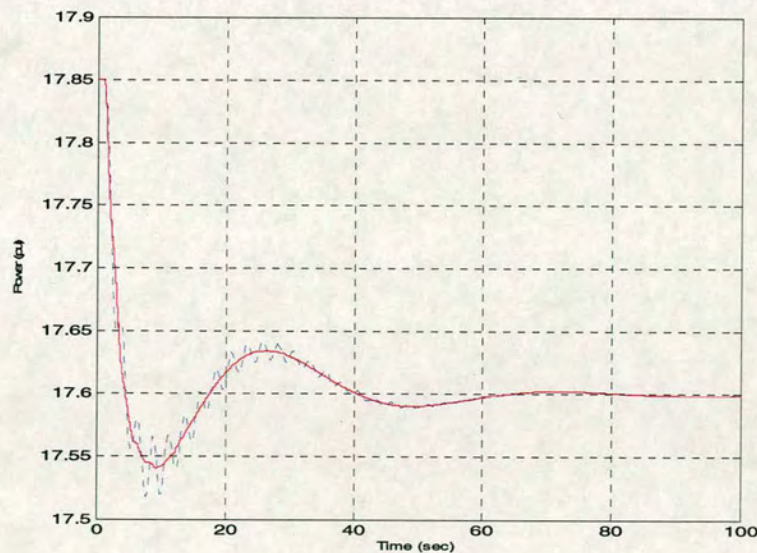


Figure C.9 Dynamic response of G15 with and without SPSS

Case 3: one of the parallel lines of the major transmission corridors between area 1 and area 2 is disconnected (bus 60-61) for fault duration of 1.6 sec ($t = 3$ sec to $t = 4.6$ sec). SPSS signals of area 1 and area 4 are assumed to be lost.

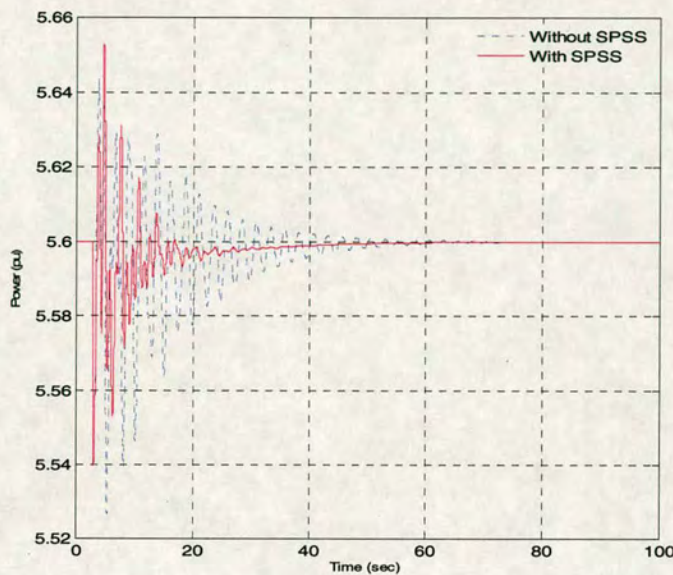


Figure C.10 Dynamic response of G7 with and without SPSS

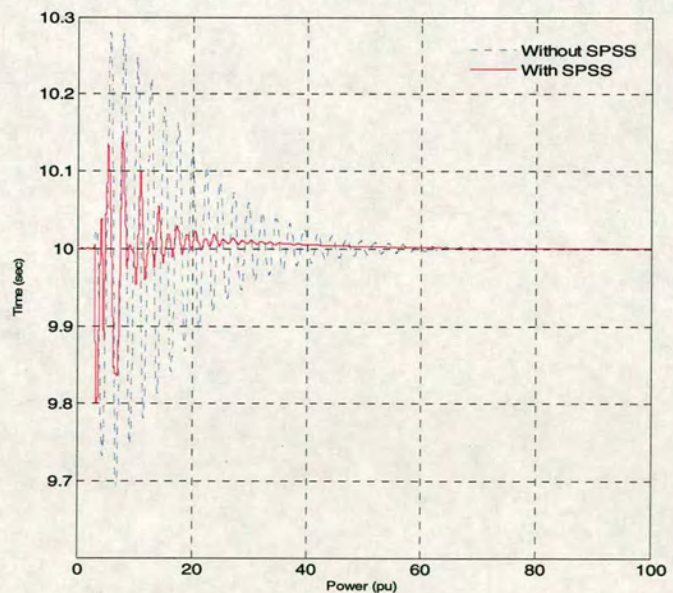


Figure C.11 Dynamic response of G15 with and without SPSS

C.1.3 Type 3 SPSS

Case 1: the generating power of G2 and G12 are reduced to 50% of its full-rated power initially while applying a unit step change of 0.05% to voltage reference of G16.

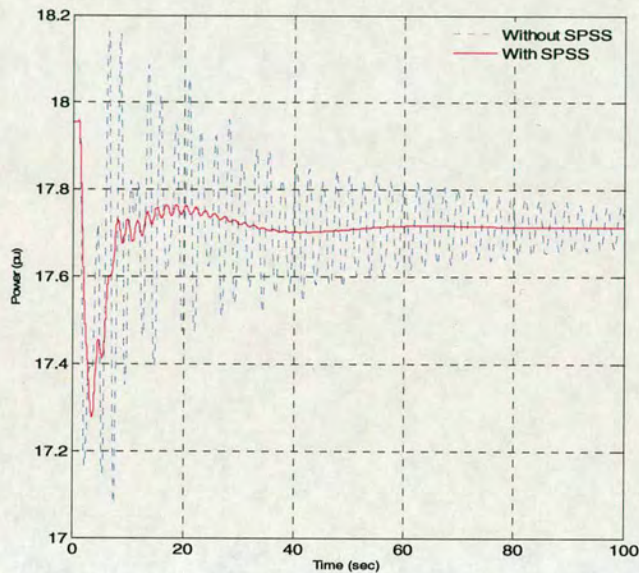


Figure C.12 Dynamic response of G13 with and without SPSS

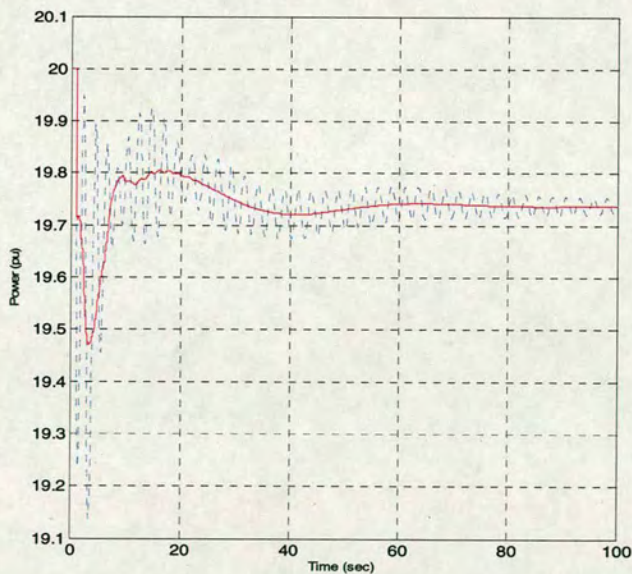


Figure C.13 Dynamic response of G16 with and without SPSS

Case 2: G10 is disconnected at $t = 3$ sec and the loads are unchanged.

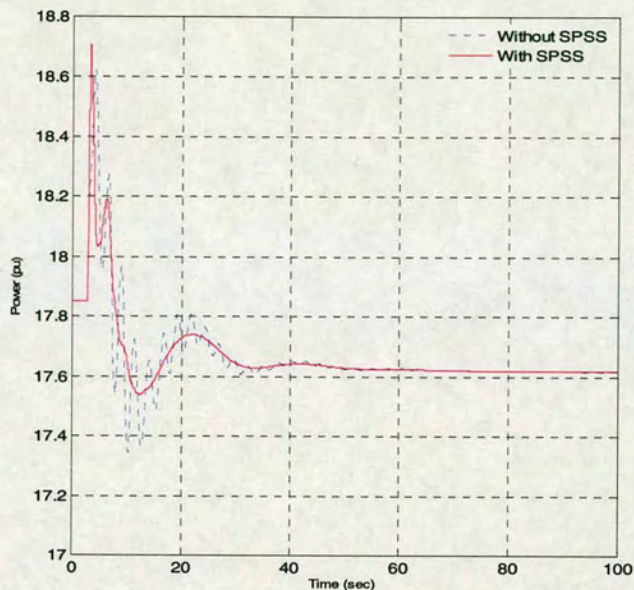


Figure C.14 Dynamic response of G14 with and without SPSS

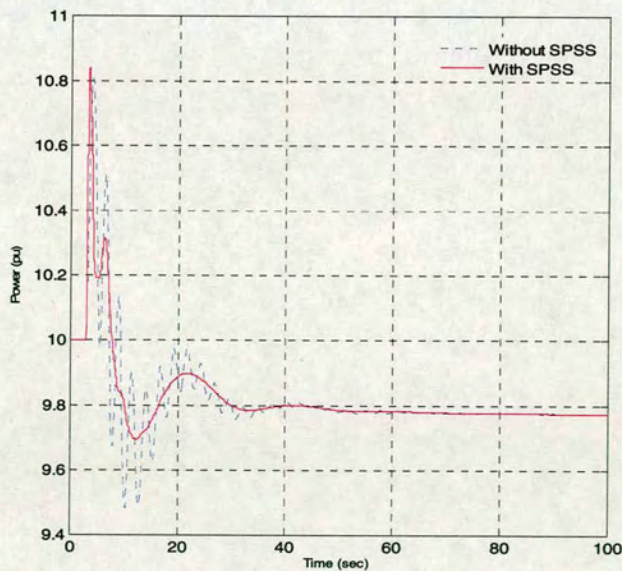


Figure C.15 Dynamic response of G15 with and without SPSS

Case 3: one of the parallel lines of the major transmission corridors between area 1 and area 2 is disconnected (bus 60-61) for fault duration of 1.6 sec ($t = 3$ sec to $t = 4.6$ sec) with a time delay of 15 ms and loss of SPSS signal to area 4.

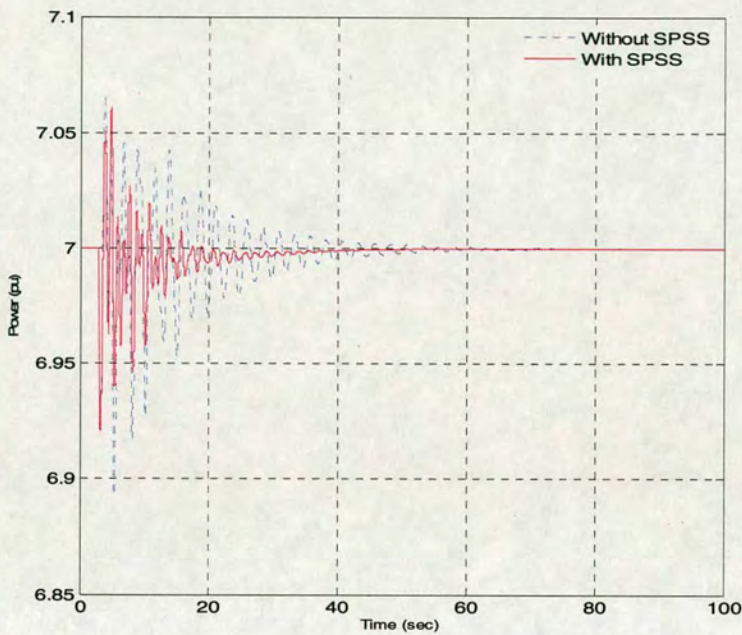


Figure C.16 Dynamic response of G6 with and without SPSS

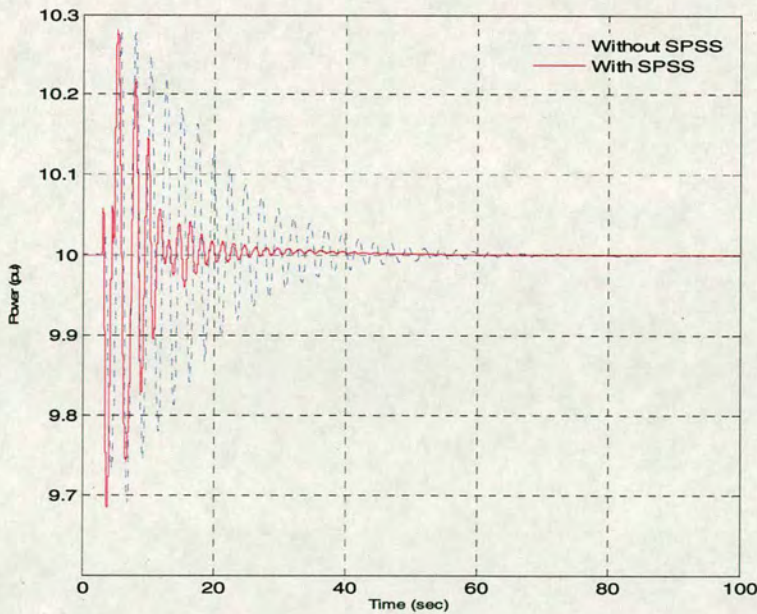


Figure C.17 Dynamic response of G15 with and without SPSS

Case 4: a three phase short circuit fault is applied at bus 60 for fault duration of 100 ms simulated at $t = 3$ s and the fault is cleared at $t = 3.1$ s. Additionally, 0.05% step change is applied to the voltage reference of G13 at $t = 3$ s prior to the short circuit.

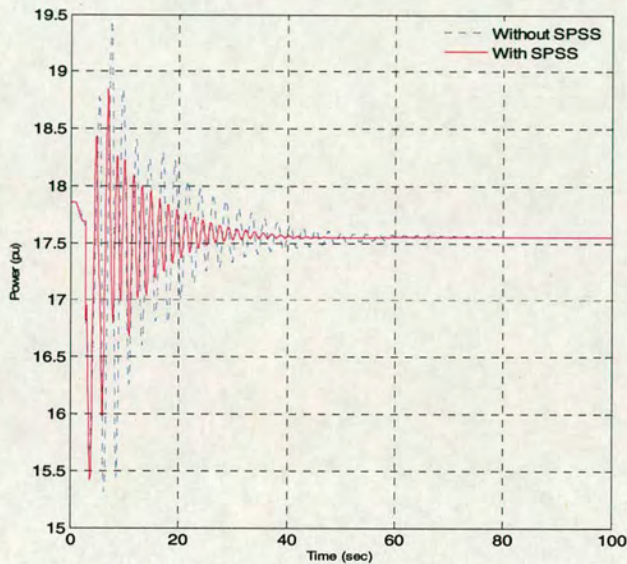


Figure C.18 Dynamic response of G14 with and without SPSS

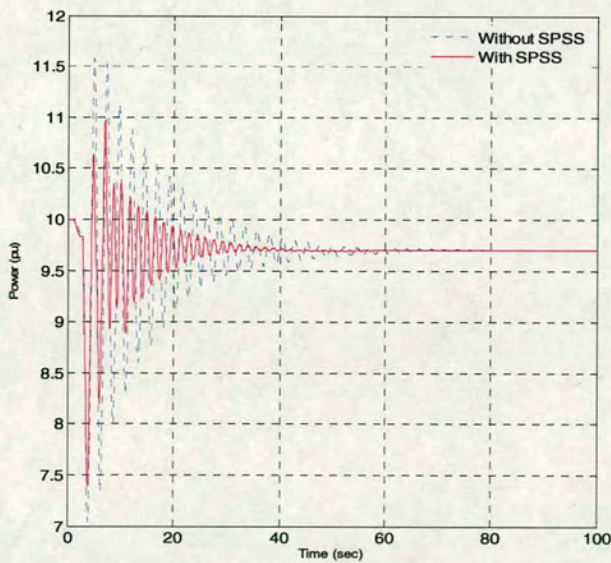


Figure C.19 Dynamic response of G15 with and without SPSS

Case 5: The initial-steady state of the test system is disturbed by a unit step change of 0.05% applied to the voltage reference of G16. The fault is created at 1.0 seconds after the start of the simulations.

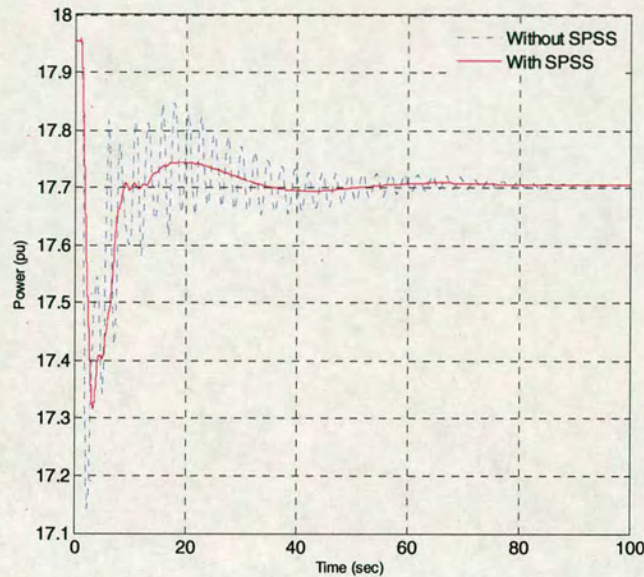


Figure C.20 Dynamic response of G13 to 0.05% step change with and without SPSS

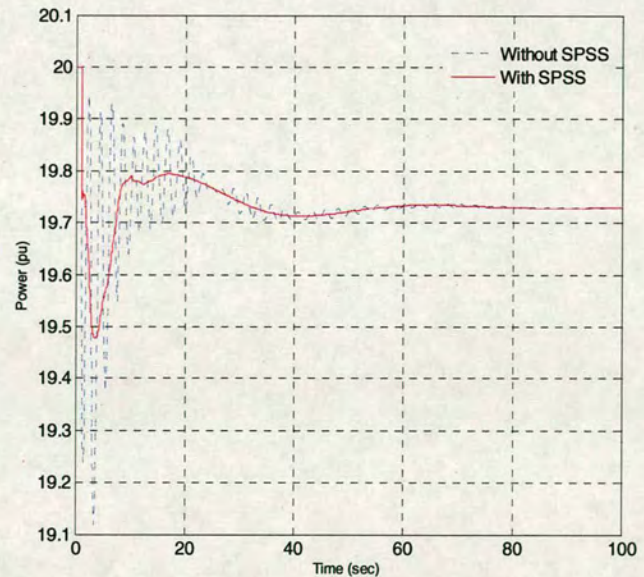


Figure C.21 Dynamic response of G16 to 0.05% step change with and without SPSS

C.2 6-Machine 3-Area Test System

C.2.1 Type 1 SPSS

Case 1: One of the parallel lines between bus no 7 and bus no 8 is disconnected for fault duration of 1.6 s. Simulation is done with time delay of 10 ms and assumption of no loss of SPSS signals.

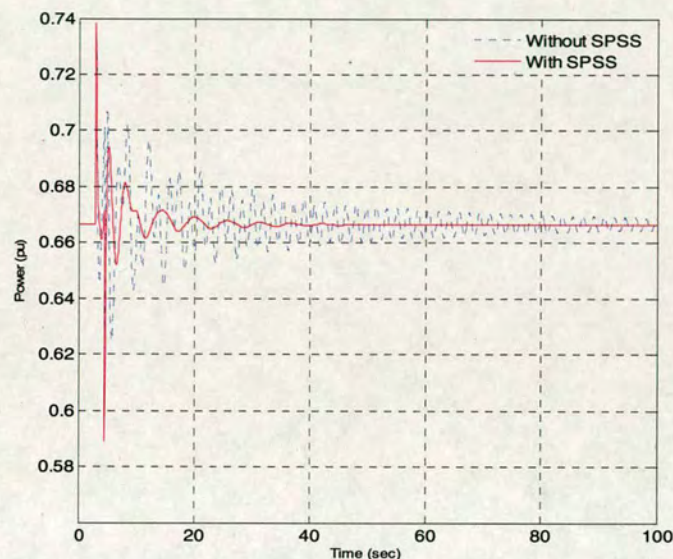


Figure C.22 Dynamic response of G2 with and without SPSS

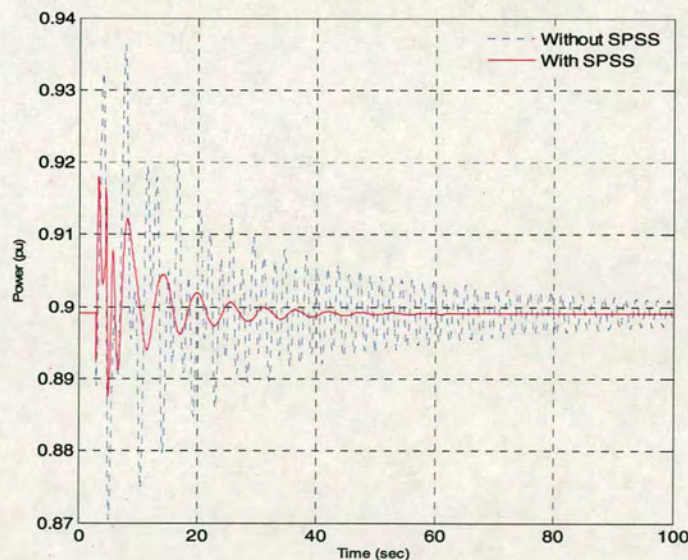


Figure C.23 Dynamic response of G5 with and without SPSS

Case 2: a short circuit is applied at bus no 7 for fault duration 100 ms.

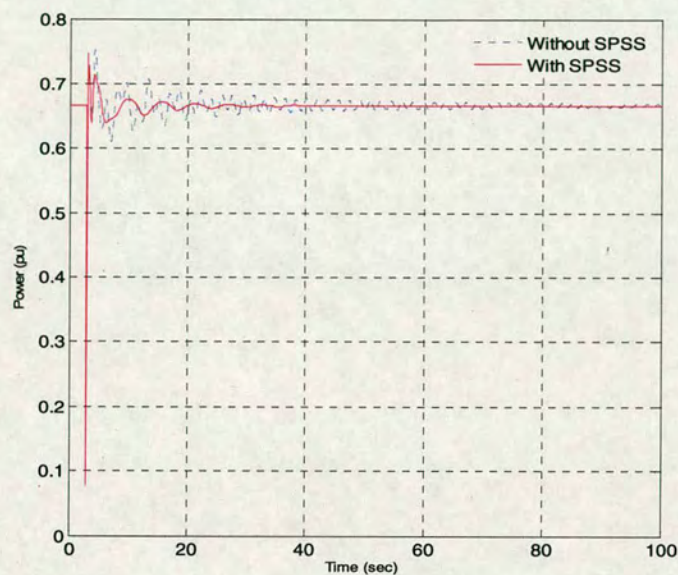


Figure C.24 Dynamic response of G2 with and without SPSS

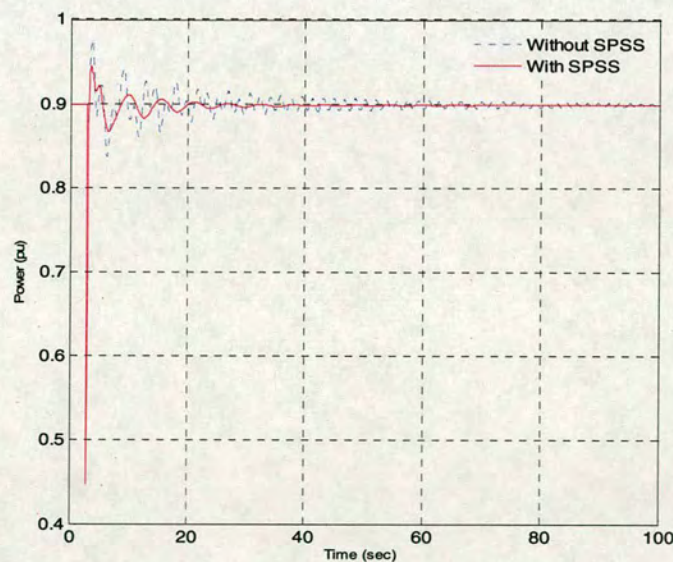


Figure C.25 Dynamic response of G5 with and without SPSS

Case 3: 0.05% unit step change is applied to voltage reference of G4 while the generating power of G2 and G4 are reduced to 50% of its full-rated power.

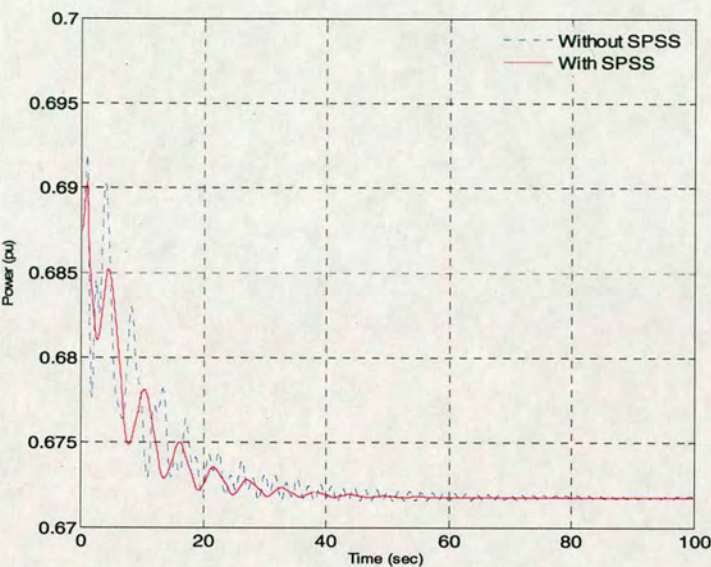


Figure C.26 Dynamic response of G3 with and without SPSS

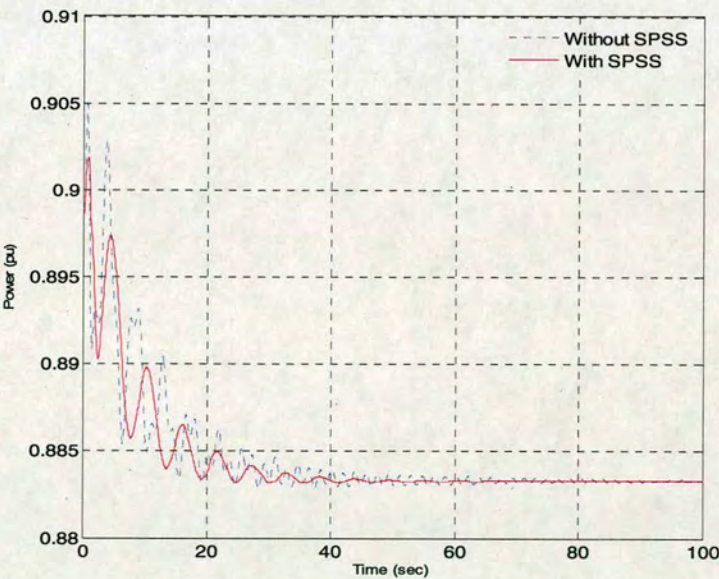


Figure C.27 Dynamic response of G5 with and without SPSS

C.2.2 Type 2 SPSS

Case 1: 0.05% unit step is applied to voltage reference of G6 with time delay of 15 ms. The system is unstable without SPSS especially with heavy bulk power exchange and very weakly interconnected system.

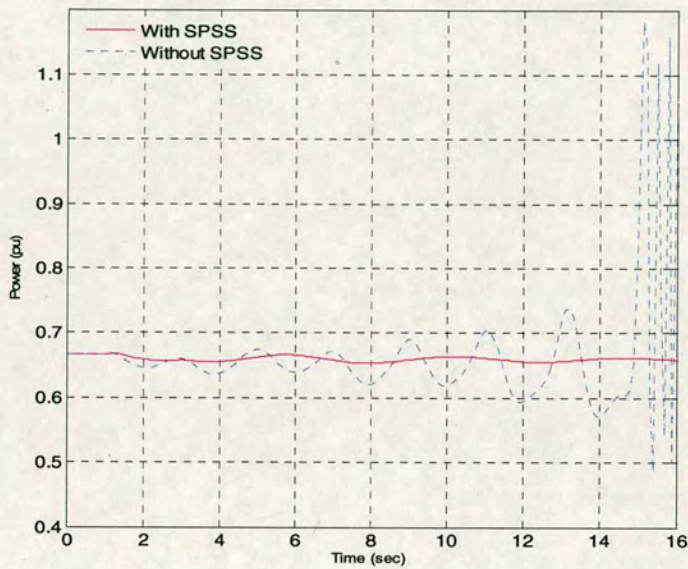


Figure C.28 Dynamic response of G4 with and without SPSS

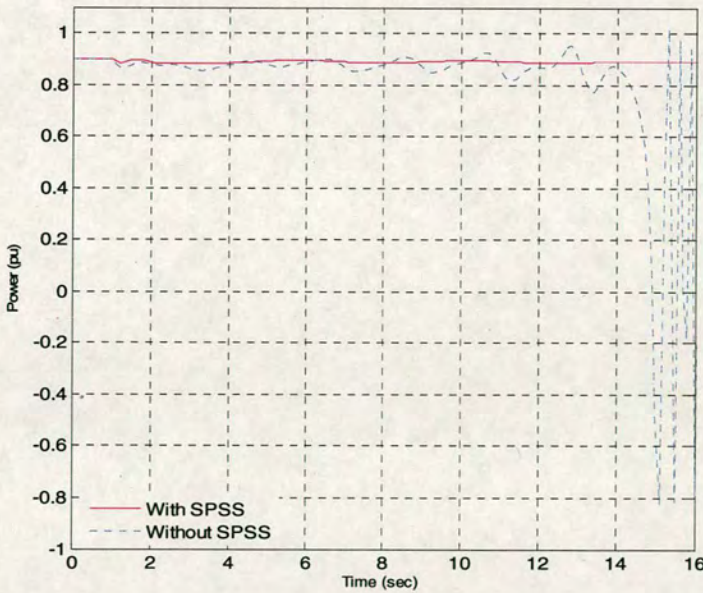


Figure C.29 Dynamic response of G6 with and without SPSS

Case 2: a short circuit is applied at bus no 7 for fault duration of 100 ms

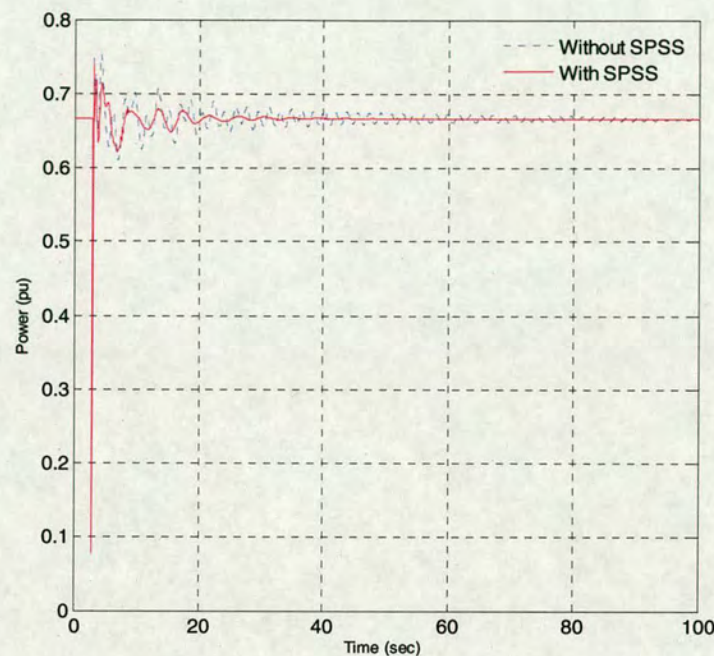


Figure C.30 Dynamic response of G2 with and without SPSS

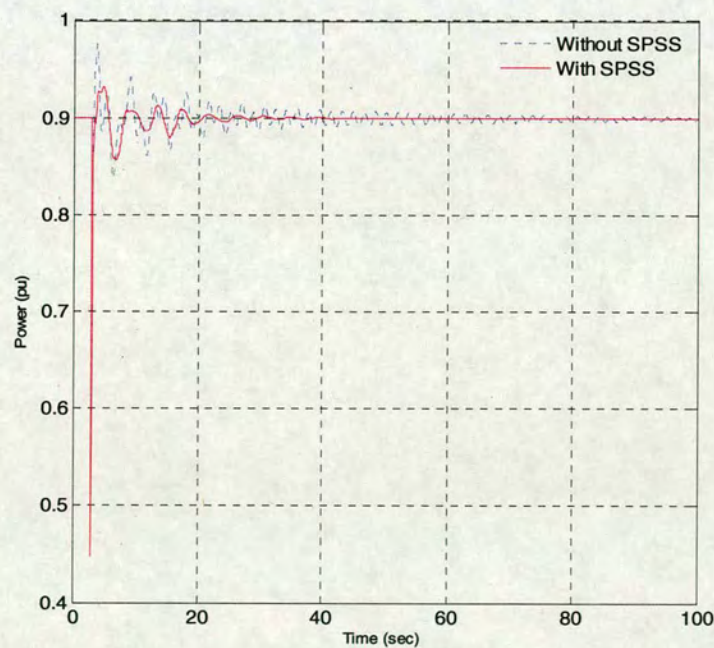


Figure C.31 Dynamic response of G5 with and without SPSS

Case 3: One of the parallel lines between bus no 7 and bus no 8 is disconnected for 1.6 s while there is a loss of SPSS signal to area 2.

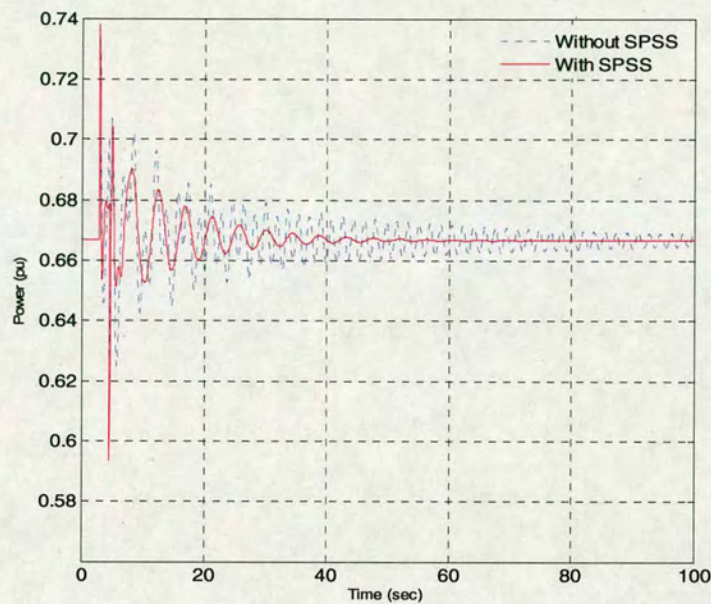


Figure C.32 Dynamic response of G2 with and without SPSS

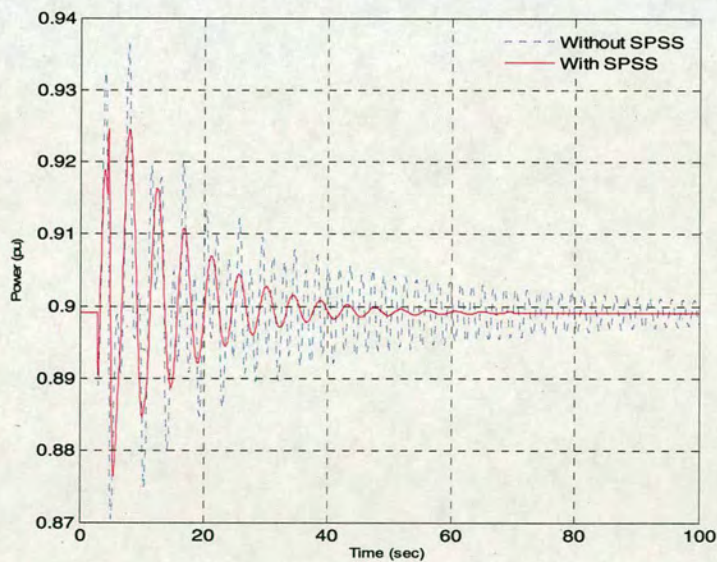


Figure C.33 Dynamic response of G5 with and without SPSS

C.2.3 Type 3 SPSS

Case 1: One of the parallel lines between bus no 7 and bus no 8 is disconnected for 1.6 s. Some SPSS signals to G4 and G5 are lost.

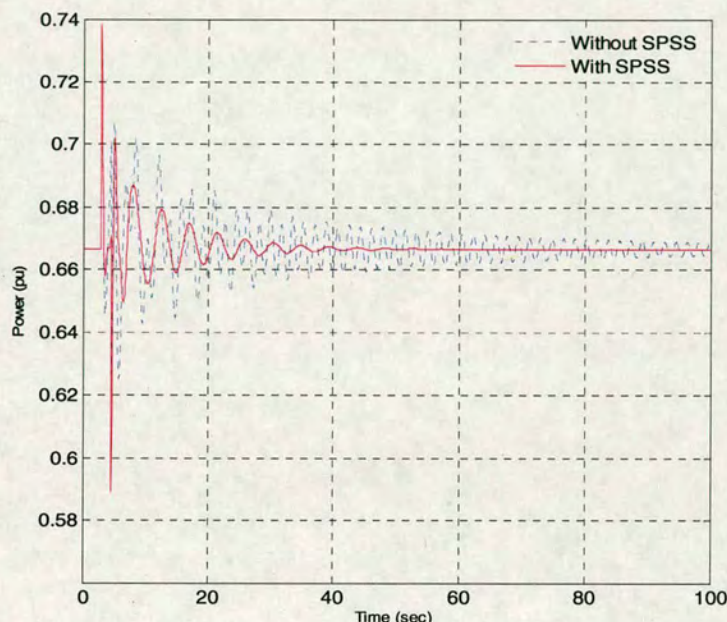


Figure C.34 Dynamic response of G2 with and without SPSS

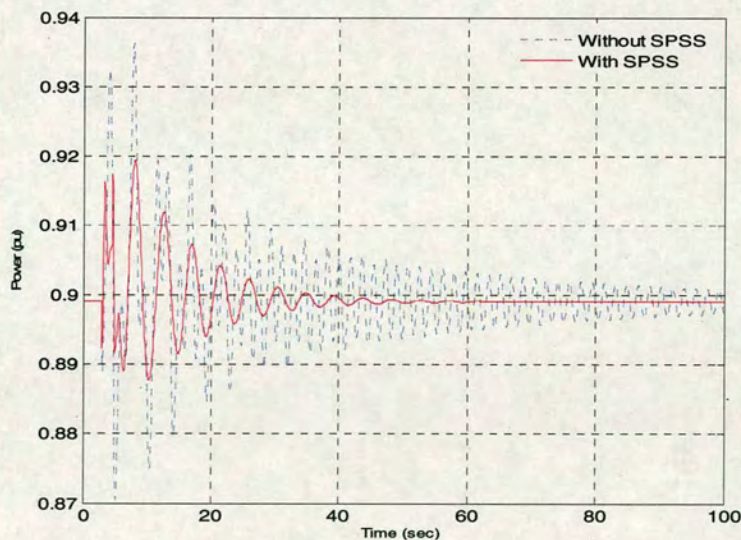


Figure C.35 Dynamic response of G5 with and without SPSS

Case 2: : 0.05% unit step is applied to voltage reference of G6 with time delay of 15 ms. The system is unstable without SPSS especially with heavy bulk power exchange and very weakly interconnected system.

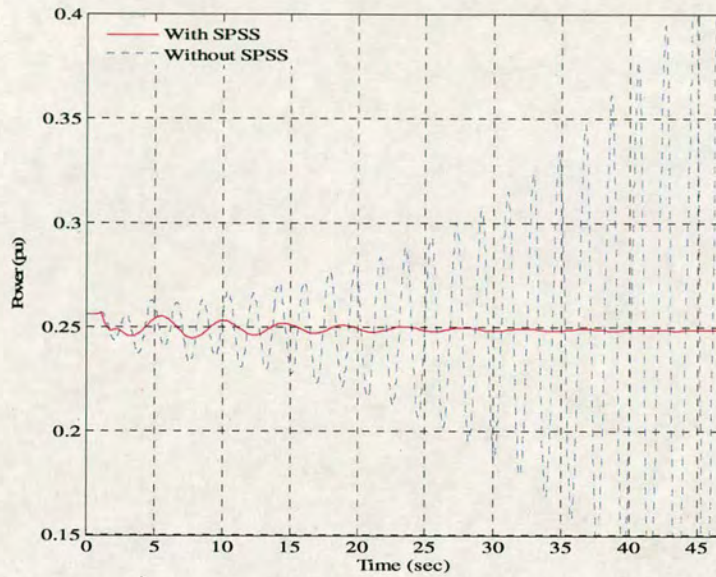


Figure C.36 Dynamic response of G1 with and without SPSS

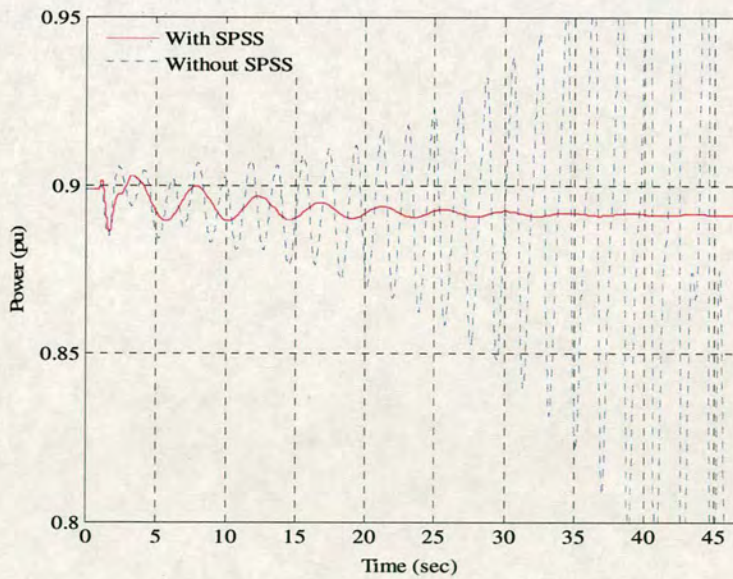


Figure C.37 Dynamic response of G6 with and without SPSS

Case 3: A short circuit is applied at bus no 7 for fault duration of 100 ms with time delay of 10 ms.

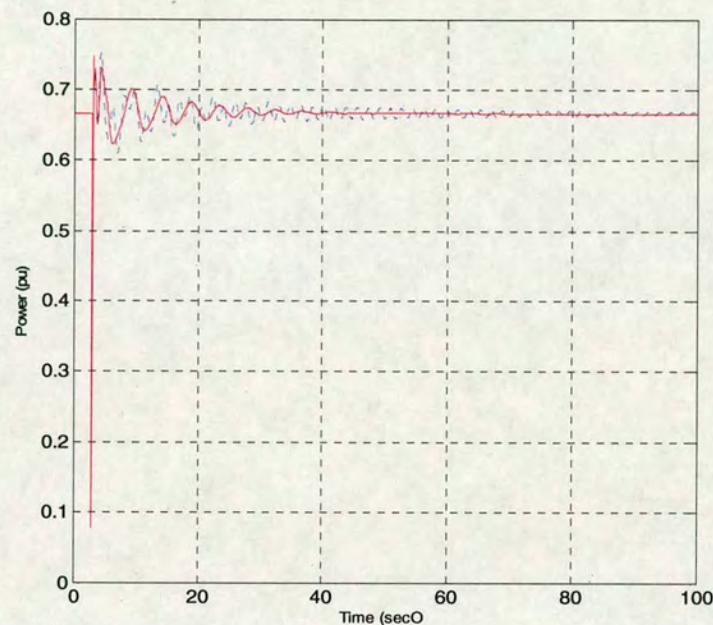


Figure C.38 Dynamic response of G2 with and without SPSS

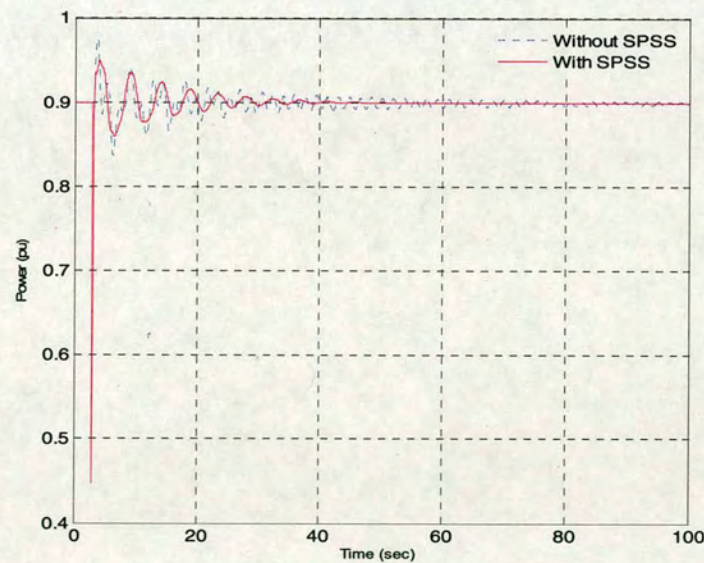


Figure C.39 Dynamic response of G5 with and without SPSS

C.3 4-Machine 2-Area Test System

Case 1: one of the parallel lines between area 1 and 2 is disconnected (i.e. bus no. 7-8) for fault duration of 3 s and time delay of 10 ms.

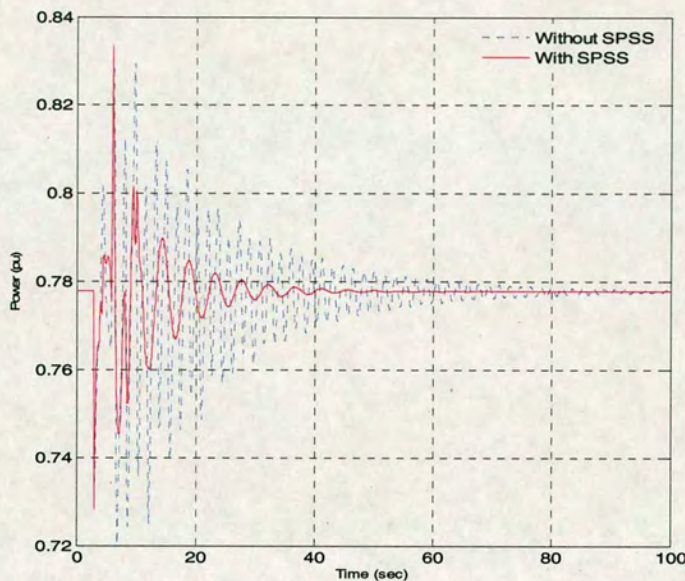


Figure C.40 Dynamic response of G2 with and without SPSS

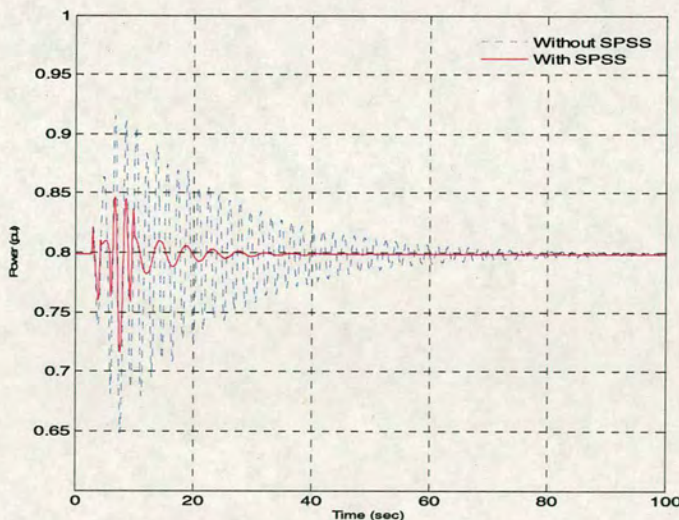


Figure C.41 Dynamic response of G3 with and without SPSS

Case 2: a short circuit is applied at bus number 7 for fault duration 100 ms with the assumption no loss of SPSS signal.

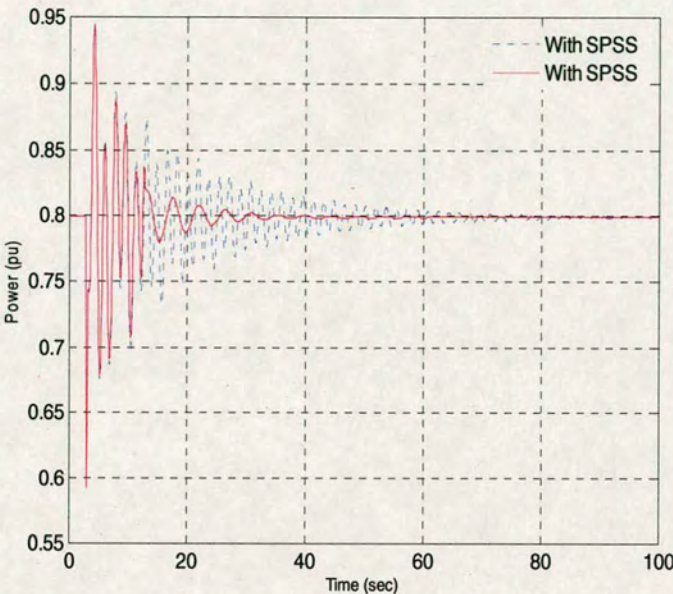


Figure C.42 Dynamic response of G3 with and without SPSS

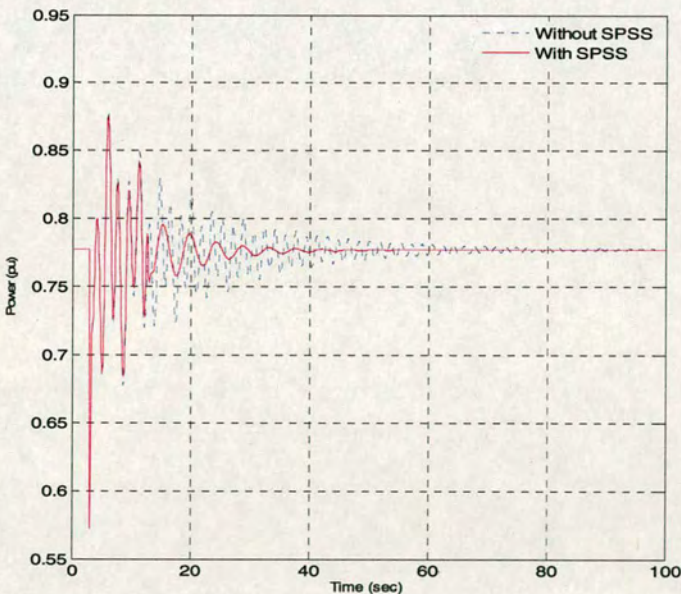


Figure C.43 Dynamic response of G4 with and without SPSS

Case 3: one of the parallel lines between area 1 and 2 is disconnected (i.e. bus no. 7-8) for fault duration of 1.6 s and a loss of SPSS signals to G1 and G4.

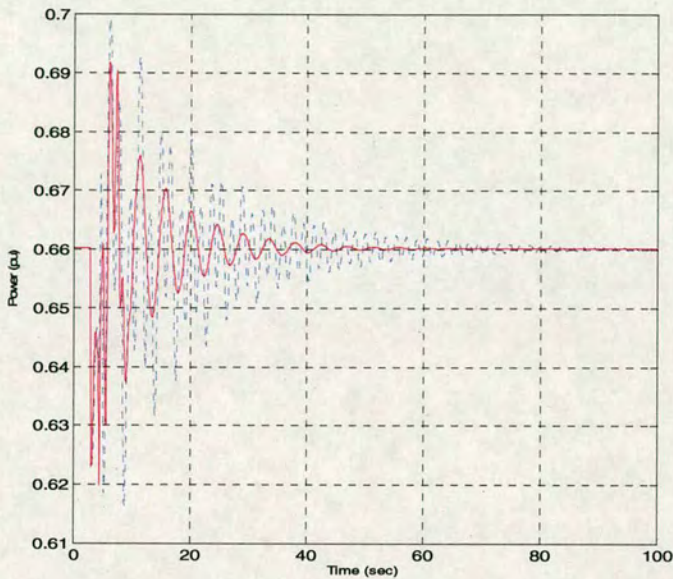


Figure C.44 Dynamic response of G1 with and without SPSS

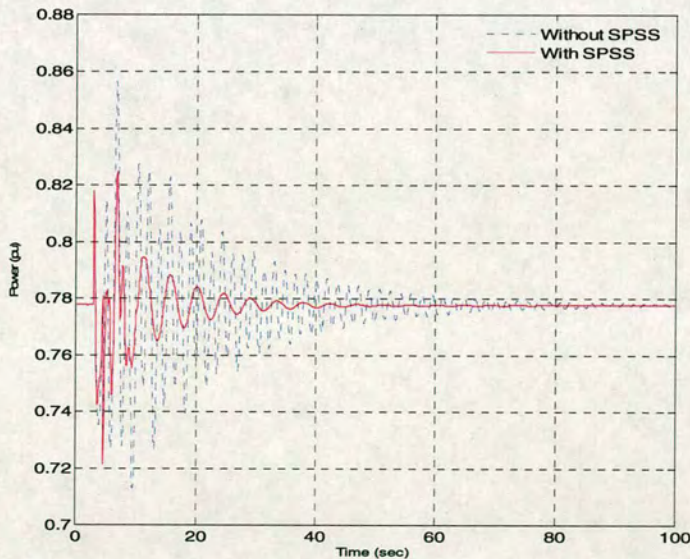


Figure C.45 Dynamic response of G4 with and without SPSS

Case 4: 0.05% unit step change to voltage reference of G4 at $t = 1$ sec with a load increase of L7 to 1200 MW.

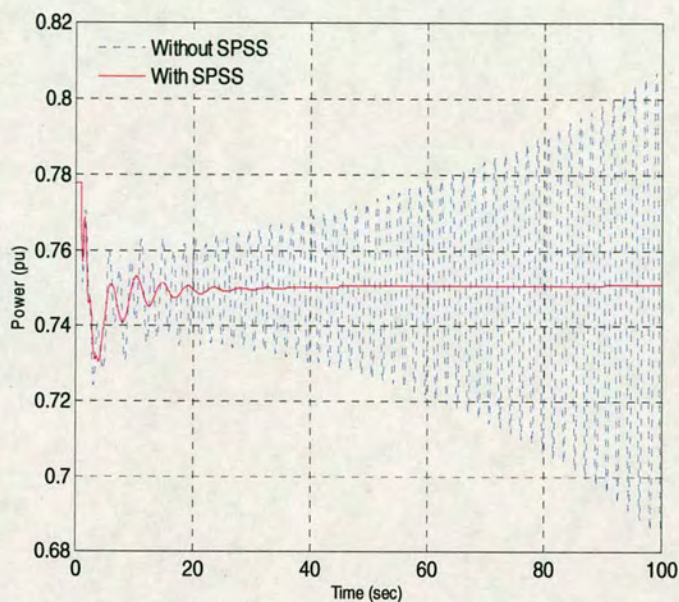


Figure C.46 Dynamic response of G4 with and without SPSS

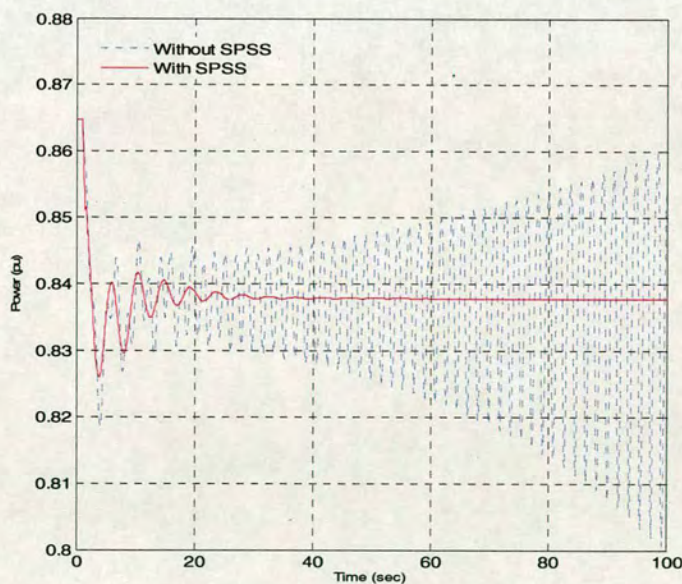


Figure C.47 Dynamic response of G1 with and without SPSS

List of Publications

[1] Hussain Behbehani, Zbigniew Lubosny and Janusz Bialek, "Survey of Supervisory Power System Stabilizers for Enhancement of Power System Stability," Presented to UPEC Conference Proceedings, Brighton, UK, September 2007.

[2] Hussain Behbehani, Zbigniew Lubosny and Janusz Bialek, "Enhancement of Power System Stability Using Fuzzy Logic Based Supervisory Power System Stabilizer," Abstract. The 2nd IEEE International Power and Energy Conference, Johor Bahru, Malaysia, December 1-3, 2008.